IASPEI (Seismology, Geophysics)

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IUGG-1112

A scheme to set preferred magnitudes in the ISC Bulletin

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The International Seismological Centre (ISC), thanks to a unique international cooperation in the seismological community, collects, integrates and finally processes seismological bulletins (location parameters, seismic station data, moment tensor solutions, felt reports, etc.) from about 130 agencies around the world to produce the ISC Bulletin, which is considered the most comprehensive worldwide summary of seismic events, both natural and anthropogenic.

Users of the ISC Bulletin and related products (e.g., EHB Bulletin) often find several magnitude estimations for a single seismic event reported by the ISC and other agencies, particularly for large earthquakes. It is not unusual that the magnitude population includes not only different magnitude types (e.g., mb, Mw, Ms, Ml), but also more than one magnitude for a given magnitude type. Since it may not be straightforward for ISC users to select the appropriate magnitude(s) for different types of studies or uses of ISC data, we started to set up a scheme to assign preferred magnitude flags within the magnitude population of a seismic event. Our scheme tries first to select the preferred magnitude for a given type when more magnitudes are available for one type. This is done by considering different factors, such as network coverage, uncertainty, knowledge of the agency practice, etc. Then, among the preferred magnitudes, we select the event prime magnitude by giving priority, if available, to standard teleseismic estimations (e.g., Mw, Ms, mb) over regional/local magnitudes types (e.g., Ml, mbLg, Md, etc). We trust that once implemented in ISC routine operations, such scheme will help ISC users to get a better tailored output from the various datasets available at the ISC web site (www.isc.ac.uk)

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IUGG-1851

Costa Rica seismic catalogue from April 1984 until October 2014

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In this work we analyzed the Costa Rica seismic catalogue from April 1984 until October 2014, collected by the Observatorio Sismologico y Vulcanologico de Costa Rica, Universidad Nacional de Costa Rica (OVSICORI-UNA) network. We analyzed the completed of the catalogue, magnitude homogenization, earthquakes parameters qualities assessments, spatio-temporal seismic distribution, energy released and seismic stations distribution in time.

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IUGG-3685

The European-Mediterranean RCMT Catalog: 18 years of data

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In the European-Mediterranean region also a moderate magnitude event may be particularly relevant due to the high seismic hazard of most of this region. The RCMT project is the most relevant and most continuous initiative for moderate magnitude seismic moment tensor computation in the Euro-Mediterranean scale. It starts with the 1997-1998 Central Italy seismic sequence, when Ardvisson and Ekström (1998) have already developed the regional version of Centroid Moment Tensor (CMT) computation technique, based on the modeling of surface waves of intermediate period (35-100 s) recorded at regional distance. The method focuses on the determination of a centroid moment tensor also for moderate magnitude events, e.g. a magnitude between 4.5 and 5.5, while standard CMT points to solve for earthquakes with a magnitude greater than 5.5. It is applied to all earthquakes with this magnitude occurring between the Gibraltar Strait to the Middle East countries, from the Northern Africa to Northern Europe. So, after 18 years of activity, a total of nearly 1700 RCMTs are available now in the Catalog that, added to standard CMT, represents the richest and homogeneous database of this region. A review of the Catalog features (e.g. completness, regional and over the entire Catalog) and of the possible applications of this data (e.g. seismotectonics and geodynamics analyses) will be shown.

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IUGG-3932

International Seismological Centre (ISC): Mission and products

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The International Seismological Centre (ISC) is a non-governmental non-profit-making organization funded by 62 research and operational institutions in 45 countries. The ISC is charged with the production of the ISC Bulletin – the definitive summary of the global seismicity based on reports from over 130 seismic networks worldwide. We also distribute the EHB bulletin – a groomed subset of the ISC Bulletin widely used in studies of inner structure of the Earth. Jointly with NEIC, the ISC runs the International Seismograph Station Registry (IR). The IR station codes and ISC event hypocenters are used by IRIS DMC in serving seismic waveform data to its users. The ISC also updates and maintains the IASPEI Reference Event List (GT). The ISC-GEM Catalogue is another ISC dataset that was designed to be used for global and regional studies of seismic hazard and risk. The ISC Event Bibliography is an interactive facility that enables searches for references to scientific articles devoted to specific natural and anthropogenic seismic events that occurred within a region and time period of interest. The ISC also runs the registry of international contacts in Seismology. The multitude of ISC data are freely available and widely used in different fields of geophysical research.

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IUGG-0496

Seismic monitoring in the European Arctic: first results of a Cooperative project

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We present some results of cooperative monitoring seismicity of the European Arctic. The current network includes the arrays in Apatity (APA), northern Norway (ARCES), Spitsbergen (SPI) and number of single stations. The stations of the Archangelsk network such as ZFI. AMD, etc. are extremely important for improving the locations of seismic events in this region. The station ZFI is situated on Franz-Joseph Land and the station AMD is located at the coast of the Kara Sea. Recent seismic observations prove the existence of significant seismicity in the European Arctic. We show detailed studies of the seismicity around the archipelagos Spitsbergen, Franz-Joseph Land and Novaya Zemlya.

We also note that the vast majority of the events along the Gakkel Ridge have been located slightly to the south of the ridge using the regional network. We interpret this as an effect of the lack of recording stations closer to and north of the Gakkel Ridge, and the use of a one-dimensional velocity model, which is not fully representative for travel-times along the observed propagation paths. This joint Russian-Norwegian project will further focus on investigation of the crustal and upper mantle velocity structure using the seismic events observed by the integrated network of stations operated by different countries in the European Arctic. This virtual network will significantly increase the seismic monitoring capability for this region.

This research is carried out within the international Russian-Norwegian project of RUSSIAN FOUNDATION FOR BASIC RESEARCH ?14-05-93080 «Seismological research related to geophysical processes in the European Arctic»

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IUGG-0974

Role of the Egyptian National Seismological Network to Mitigate the Seismic Hazard in Egypt

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After Cairo Earthquake in 1992 (Ms 5.8), the government established the Egyptian National Seismological Network (ENSN) organized by National Research Institute of Astronomy and Geophysics (NRIAG), start to work since 1997; NRIAG has a real monitoring of the seismological activity in and around different parts of Egypt. Egypt is located within zone of the plate boundaries, in the southeastern side, the Red Sea Rift which is a zone of plate separation along which sea floor spreading separates the African plate and Arabian plates apart, from the northeastern part, the Gulf of Aqaba–Dead Sea transform fault, which is a major left-lateral strike slip fault, which accommodates the motion between the Africa, Arabian and Eurasian plates, from the north Egypt is bounded by the subduction zone where, the African plate subduct beneath the Eurasian plate the at the Cyprean and Hellenic Arcs, relative motions along these boundaries are the reason for tectonic deformation within Egypt. Egypt witnessed a numerous of damaged event, for instance, 1992 Cairo earthquake with magnitude (5.9 mb) caught the Egyptian people. This earthquake caused 600 deaths, 10000 injured and left a damage of more than 40 million US$. As a result of this damage. As well as 1995 Gulf of Aqaba earthquake with Mw 7.2. The Egyptian Government supports the National Research Institute of Astronomy and Geophysics (NRIAG) to install the Egyptian National Seismic Network ENSN and the strong motion network. The main objectives of the network are: Monitoring local and regional activity including artificial events, assessment seismic hazard, estimating the expected future earthquake effects and protecting strategic buildings, high dam and archeological sites.

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IUGG-1116

Extension of the ISC-GEM Global Earthquake Instrumental Catalogue, an update

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In this contribution we illustrate recent progress made in extending the ISC-GEM Global Instrumental Earthquake Catalogue. The first release of the ISC-GEM catalogue (1900-2009) was made available via the ISC website (www.isc.ac.uk/iscgem/index.php) in January 2013 after a 27-month project funded by the GEM Foundation (www.globalquakemodel.org). The catalogue was required to improve basic earthquake parameters, such as location and magnitude, for large global earthquakes that occurred during the instrumental period for use in seismic hazard and Earth seismicity studies.

Due to time and resource limitation, in its first releases the ISC-GEM catalogue included global large earthquakes with Ms ≥ 7.5 until the end of 1917, then earthquakes having magnitude down to 6.25 and 5.5 for earthquakes during the periods 1918-1959 and 1960-2009, respectively. Funding from GEM and two commercial companies in the US and UK allowed us to start working on an extension of the ISC-GEM catalogue, both for earthquakes that occurred beyond 2009 and for earthquakes smaller than 6.25 listed in the International Seismological Summary before 1960. This extension is part of a four-year program. During the first year we added over 1000 earthquakes that occurred in 2010-2011 and several hundreds more between 1950 and 1959. The catalogue extension between 1935 and 1949 is currently underway. Such work will also be helpful for regional, cross-border, seismic hazard studies as the ISC-GEM catalogue should be used as basis for cross-checking the consistency in location and magnitude of those earthquakes listed both in the ISC-GEM global catalogue and in regional catalogues

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IUGG-1656

Earthquake and tsunami hazards from potential earthquakes in South China Sea and its early warning implementation

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In South China Sea, the Manila subduction zone west of Philippine was identified as the most hazardous tsunami source region. Numerical simulations have shown that potential megathrust earthquakes may excite large tsunami to propagate over the whole South China Sea and induce large damages in its surrounding coast. And more dangerously, no operational tsunami warning system is available in this region till now. Once a tsunageneric earthquake occurs, there is no effective way to release an early warning, predict arrival time and tsunami high and evacuate residents in the coastal region. A discussion to propose earthquake and tsunami early warning system is necessary to reduce related hazards in the near future. In this presentation, a prototype early warning system based on a regional seismic network surrounding South China Sea has been introduced to identify the tsunami source and evaluate tsunami potential by numerical simulation. However, to construct complete earthquake and tsunami early warning system in this region, more seismic and tsunami sensor deployment and marine research and monitoring are necessary. To face the possible natural disaster, communication within multiple disciplines of earth sciences is urgency.

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IUGG-3135

New integrated events location procedure in vast and irregular networks in a quasi real-time mode

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In recent works we (University of Trieste and Genova) have implemented the RSNI-Picker (Spallarossa et al., 2014) in the Antelope software (Boulder Real Time Technologies). In this study we would like to present its application in an irregular and vast network.

We have applied this procedure to the real-time seismicity in the North-Eastern Alps, data collected by a non homogeneous stations density network. The results has shown the inefficiency of the procedure to solve the location of events occurred in not well covered areas. A lot of procedures, partially solved this issue, dividing the entire network in small sub-networks and using only one of them for each locations. But the choice of the sub-network nearest to the epicenter could be affected by fatal errors. In this study we present an upgrade of our procedure in order to avoid these kind of problems.

After the first location made by Antelope, the new procedure read the triggered arrival times and used them as phases for a preliminary location with the NonLinLoc software. This location becomes the center of the circumference in which to select the “usable” stations for the final location.

Our upgraded procedure is applied to a reference data-set acquired by the RAN in all the Italian territory, managed by the National Civil Defense in Rome. This network is an heterogeneous ones in terms of spatial coverage and in time, in fact it is composed by triggered stations, only recently few continuous real time acquisition stations are installed. So the first location is done with a partial network, and for these features is an efficient test to study the robustness of our methodology.

Preliminary results indicate that our integrated procedure could play a fundamental rule in the location of events in real-time mode.

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IUGG-0243

Intraplate earthquakes in northeast India region: Pop-up and transverse tectonics

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The Shillong plateau and Assam valley in the northeast India intraplate region, jawed between the Himalayan collision zone to the north and Burmese subduction zone to the east, produced one great (1897, Ms 8.7, revised Mw 8.1) and four (1869, 1923, 1930 and 1943) large earthquakes (M~7.0 – 7.6). High precision 20-station broadband network data (2001-2009) are reanalyzed in this study. More than 2000 events (Mw > 1.0) were recoded; out of these some 300 earthquakes (Mw ≥3.0) are relocated by TomoDD method and some 50 fault plane solutions of the events (Mw>3.are studied by waveform inversion. The relocated seismicity and fault plane solutions shed light to understand seismotectonic model(s) of the intraplate earthquakes in this region. Dominating thrust/reverse faulting earthquakes in western part of the Shillong plateau may be explained by the proposed pop-up tectonics between two active boundary faults, the Oldham–Brahmaputra fault to the north and the Dapsi–Dauki thrust to the south, though the northern boundary fault is much debated. The more intense normal and strike-slip faulting earthquakes in the eastern plateau (Mikir massif) and in the Assam valley, on the other hand, are well explained by transverse tectonics along the long and deep rooted Kopili fault that cuts across the eastern Himalaya and caused the 2009 Bhutan earthquake (Mw 6.3). It is conjectured that the pop-up tectonics of the Shillong plateau and transverse tectonics along the Kopili fault in the Assam valley make the region vulnerable for impending large earthquake.

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IUGG-1144

Seismic activity in Iran, during 2014

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The Iranian plateau is one of the most seismically active areas in the world and frequently suffers destructive and catastrophic damage. In Iran, a destructive earthquake occurs every few years because it is situated over a seismic zone and does not appear to be a single crustal block, and shortening is thought to be concentrated in the three main active belts of Zagros, Kopeh-Dagh–Alborz–Talesh, and Central Iran and the Dasht-e-Lut Basin. Seismic analyses and the study of seismotectonic structure relying on the seismic records obtained during 2014, several seismically active areas could be recognized. The epicenters of local earthquakes are in good agreement with the location of major faults as well as the regional tectonic settings .Distributions of epicenters indicate high seismic activities in region and The distribution of earthquakes in eastern and western parts of the region are consistent with the related major faults. Geological evidences and fault plane solutions of earthquakes in Iranian Plateau is predominantly thrust mechanism but in eastern and northen regions indicate the existence of both thrust and conjugate strike-slip faulting. The majorities of earthquakes have reverse source mechanism with strike-slip component and are in agreement with convergent motion of Arabian plate. The direction of pressure axes follow the northeast direction but there are indication of some local changes due to complex fault systems. A major activity is in Alborz and Zagros region but Lut- Block, Central Iran and the Caspian Block are aseismic. Zagros has more seismic energy release than the other regions. The comparison of seismic energy maps indicates that the seismic gaps in early intervals were filled up by the seismic activities during the following time intervals.

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IUGG-2391

Identification of Active Structures In the Cilician Region Using High Resolution Earthquake Locations

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Double difference algorithm was applied to 4554 earthquakes with local magnitudes ($M_L \leq 5.0$) in the Cilician region, southeastern Turkey. These events were collected within the scope of a multilateral project continuing from 2007 to 2011. Study area was divided into four sub-regions (A, B, C and D) in order to reveal detailed images of active tectonic structures in each sub region. In the region A, we determined an alignment in depth along the cross section C-C´, suggesting this structure is dipping to the SW with a strike of ~330°. This observation is in agreement with NNW-SSE trending normal mechanisms obtained in this study. The region B has a distinct small cluster, showing a clear NE-SW trend on the map view. Earthquakes in this region were located at depths of 20-35 km. Cross sections of A-A´ and C-C´ in the region C show that earthquakes were localized at two different depths for possible fault-perpendicular strikes. Localization of accurately located hypocenters at a single depth along the cross section A-A´ indicates presence of a NW-SE trending dextral strike slip fault which is observed at a shallow depth. In the D region there is obvious alignment of earthquake epicenters following the East Anatolian Fault (EAF) and its branches. Also, vertical alignments of earthquake hypocenters were observed along the cross-sections A-A´, C-C´ and D-D´. This observation is consistent with left lateral strike slip focal mechanism solutions, being active in the region. The double difference method has been useful in resolving structural details of active faults in the study area.

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IUGG-2641

Modelling segmented-fault earthquakes using full-scale, topological inversion of GPS data: the case of the Leucas 2003 earthquake, NW Aegean Arc

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Certain fault complexities can be approximated by a fault consisting of two (or more) segments. In the case of co-seismic surface displacements, measured by GPS, such fault pattern can be described by the Okada equations, but no formal solution/inversion of this problem/system is usually possible. Various techniques, such as searching/sampling in the vicinity of an approximate solution or assuming a priori constrained (fixed) variables, have been used so far yet may not leading to optimal-unbiased solutions or global solutions.

An alternative approach, the TOPological INVersion algorithm, has recently been proposed to solve this problem. Using independent, seismological constraints, a hyper-grid G is formed in the R^n (n unknown variables) space including all the possible solutions. On the basis of observation uncertainties, of an optimization parameter k and using Boolean logic, it is tested which of the grid-points satisfy the system of equations. Minimization of k by repeated tests permits to approximate the solution with closed set of grid-points. Then using stochastic techniques the best solution and uncertainties are obtained.

The new algorithm was applied in the modelling of the 2003 Leucas (Ionian Sea, Greece) earthquake (Mw 6.2) along the Cephalonia Transform Fault, at the NW edge of the Hellenic Arc. This seismic sequence represents a matter of debate among scientists, while the analysis of GPS data had not led to a satisfactory solution. The new algorithm permitted to recognize two en echelon oblique-slip fault segments correlating with the clusters of epicentres and consistent with certain seismological models, and hence to shed more light in a seismic sequence with sub-optimal distribution of geodetic and seismologic observation stations.

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IUGG-2824

Concerning the origin of the 2014 January 17 earthquake (Mw=4.3) on the Siberian platform

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We described the 2014 January 17 earthquake (M_w=4.3) occurred on the Siberian platform in the area of sublongitudinal part of the Angara river in the zone of possible influence of two large reservoirs – Ust-Ilimsk and Boguchan. This is the first event of such magnitude recorded in this previously aseismic area during the whole period of instrumental observations. A seismic moment, a moment magnitude, a hypocentral depth and a focal mechanism of the event were calculated on the basis of surface wave amplitude spectra. Analysis of the geological and geophysical data showed that the earthquake origin is connected with high velocity gradient zone located at the border of the Late Proterozoic cover and the Precambrian basement of the Siberian platform. Some evidences for a natural character of the earthquake were considered.
This study was supported by the RFBR grant 14-05-31173.

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IUGG-2109

Focal mechanisms of weak events from polarities and waveforms, new approaches demonstrated on a rare Mw 4.3 event in Brazil

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Focal mechanisms of relatively weak events are important, e.g. for the stress estimates in intraplate regions, or in forensic seismology. However, their determination is difficult if events are infrequent and seismic networks are sparse. A recently suggested approach consists of combining polarities and waveforms. It starts with a suite of first-motion polarity solutions (provided, for example, by FOCMEC code; Snoke 2003), which is further constrained by full waveform inversion (CSPS method, Fojtikova and Zahradnik, 2014). Importantly, even few stations may efficiently reduce the uncertainty of the FOCMEC suite if the waveforms can be successfully modeled. Scalar moment is the bonus of the waveform inversion. In this contribution we analyze pros and cons of the CSPS method using as example a rare event in central Brazil. It is the Mw 4.3 mainshock of the Mara Rosa 2010 earthquake sequence, one of the first few GT5 (Ground Truth) earthquakes in Brazil (Barros et al., 2014, Carvalho et al., 2015). A particularly emphasized topic is the uncertainty of take-off angles, and their effect upon the FOCMEC and CSPS solutions. A routine approach is to use the angles determined along with the event location. The angles correspond to the first arriving P phase, either Pg or Pn. We show that such a formal approach may be problematic. To this goal we analyze variations of the take-off angles with epicentral distance and source depth in several crustal models (the layers with constant velocity, or velocity increasing with depth, with and without intra-crustal discontinuities). These aspects, often badly overlooked in practice, are analyzed with two aims: (i) to improve focal mechanism of the Mara Rosa mainshock, and (ii) to formulate recommendations of a broader applicability.

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IUGG-3547

Seafloor observation network for earthquakes and tsunamis along the Japan trench (S-net)

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Huge tsunami, which was generated by the 2011 off the Pacific Coast of Tohoku Earthquake (Mw9.0), attacked the coastal areas in the north-eastern Japan and gave severe casualties and property damages. Before this disaster, there were poor on-line read-time seismic and tsunami observation networks in sea area around Japan, and information of ground motion and tsunami heights were very limited. To break this serious situation, the project to construct a large-scale seafloor network of cable-linked observatories around Japan Trench and Kuril Trench, named Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net), started in 2011. This network is for earthquakes, tsunamis and vertical crustal deformations. Such real-time data from the seafloor observatories make it possible to forecast the next-generation early tsunami warning which could precisely predict coastal tsunami height. Also the data may make it possible to forecast an earthquake warning much earlier than the present system.

The network consists of 150 ocean bottom observation stations. Ocean bottom fiber optic cables, about 5,700 km in total length, connect the stations to land. Observation stations with tsunami meters and seismometers will be placed on the seafloor off Hokkaido, off Tohoku and off Kanto, in a spacing of about 30 km almost in the direction of East-West (perpendicular to the trench axis) and in a spacing of about 50 - 60 km almost in the direction of North-South (parallel to the trench axis). Two or more sets of tsunami meters and seismometers will be installed in one station for redundancy. The digitized data will be transmitted to the data centers, JMA (Japan Meteorological Agency), and so on, using IP network.

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IUGG-4034

Re-analysis of the normal mode spectra of the 1960 Chile earthquake

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After the great 1960 Chile earthquake, Press et al. (1961) created a unilateral source rupture model with a length of 1000 km at a speed of 3-4km/s. Kanamori and Cipar (1974), looked at long-period motion before the main shock in the strain-meter record at ISA and hinted the existence of a slow precursor. Kanamori and Anderson (1975) interpreted that the anomalous decrease of the Fourier spectral amplitude near 1.8 and 3.0mHz of the UCLA gravimeter record the Press-Ewing seismometer record at PAS are caused by the interference between the main-shock and an un-modeled precursor. Cifuentes and Silver (1989) collected IGY seismographic data and confirmed the existence of the spectral holes at 4 stations all situated in the continental U.S. and modeled the holes with a large precursor or a post-cursor. KA75 and CS89 synthetic spectra did not consider the spheroidal-toroidal modal coupling effect. We compared the amplitude spectra computed for earthquake models of a line source and a point source, and for the PREM and a rotating elliptic Earth model with laterally heterogeneity inside. The spectra are computed for the same time series presented in CS89 and directly compared with their amplitude pattern. The observed amplitude spectrum patterns are re-produced at 8 globally distributed stations including the amplitude holes at 4 stations in the U.S by a line source for a rotating elliptic earth model with lateral heterogeneity inside. The synthetic spectrum tests indicate that the long-period precursor or post-cursor proposed by Cifuentes and Silver (1989) and Kanamori and Anderson (1975) is likely unnecessary. Even a possible post or precursor is excluded, magnitude Mw9.6 estimate by seismological methods is still larger than geodetic (Mw9.3) and tsunami (Mw9.2) estimates.

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IUGG-4704

Inferring seismicity and crustal structure by applying state-of-the-art seismic network analysis to a temporary array in Bhutan

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In this work we document how state-of-the-art network infrastructures and data analysis can be efficiently combined to derive high-quality regional earthquake catalogs, source parameters, and images of the crust in previously poorly studied regions. Virtually no information on the seismicity and crustal structure of Bhutan exists, although a minimum slip potential of ~5 m is suggested for this section of the Himalaya.

To improve the image of active faults and crustal structure of the orogen, a network of 38 broadband stations was deployed during 16 months in Bhutan. The data was integrated into the powerful SeisComP3 infrastructure of the Swiss Seismological Service, allowing efficient access and processing. The SeisComP3 software was adopted to automatically detect events in off-line mode. Manual review as well as downstream analysis like source inversions were performed. More than 600 events with ML between 0.5 and 5.6 were detected in Bhutan and surrounding regions. To improve location accuracy, a subset of events was used to compute a regional minimum 1-D P and S wave velocity model using the VELEST software. In combination with a receiver function analysis the model provides first constraints on the crustal structure. The entire catalog was relocated with the NonLinLoc software, for clusters relative relocation using the HypoDD software was performed.

Our earthquake catalog images seismotectonic processes in the region at high resolution. Compared to regional and global solutions reported in the ISC bulletin, accuracy of hypocenters is significantly improved by our network. In addition, seismicity, receiver functions and seismic velocities suggest significant differences in the crustal and tectonically active structure between East and West Bhutan.

IASPEI (Seismology, Geophysics)

S01e - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-0303

Identification of the multi-sphere sources in the coastal and marine environment inferred from infrasound array observations in East Antarctica

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Characteristic features of infrasound waves observed at Antarctica reveal physical interaction involving surface environments in the continent and Southern Ocean. A single infrasound sensor has been continuously recorded since 2008 at Syowa Station (SYO; 39E, 69S), the Lützow-Holm Bay (LHB), East Antarctica. The recording data clearly represent background oceanic signals (microbaroms) during whole seasons. In austral summer in 2013, several field stations are established along the coast of LHB. Two infrasound arrays with different diameter triangles are installed at both SYO (100 m spacing) and on continental ice sheet (1000 m spacing). Besides the arrays, isolated single stations are deployed at two outcrops. The new arrays clearly identified the predominant propagating directions in NWN and their frequency content variations of microbaroms from Southern Ocean. Microbaroms measurement is a useful tool for characterizing ocean wave climate, complementing other oceanographic and geophysical data in the Antarctic. Moreover, characteristic signals are demonstrated, such as regional earthquakes, the airburst shock waves generated from meteoroid injection at the Russian Republic on February 2013. Detail and continuous observations of infrasound waves in Antarctica is a new proxy for monitoring a environmental changes such as global warming affecting on polar regions. One objective of CTBTO is to estimate the detection and location capabilities of the network at regional and global distances, another is to enhance the understanding of wave propagation through the atmosphere. Then increasing the number of stations in Antarctica is very efficient to provide the precious data in high southern latitude.

IASPEI (Seismology, Geophysics)

S01e - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-1055

Pulsations of the oscillations of the Earth after the earthquakes

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The records from wideband seismic stations are analyzed for studying the oscillations of the Earth what emerged after the earthquakes. Attention is focused on the bands with the periods more than 20 min. Pulsations of the radial mode oSo in the interval from 5 to 7 days after the earthquakes are revealed. They have a period of 127–129 min which is twice exceeds the longest known period of free oscillations 53.9 min. The pulsations expressed worse at stations located near the poles. The phases of pulsations coincide at stations situated close to each other and have opposite polarity at stations located in eastern and western parts of the globe. The amplitudes of pulsations do not depend on the phases of tidal variations. We studied not synchronizing interactions of different Earth's free oscillations. The model based on the van der Pol equation are suggested to explain the main features of pulsations.

IASPEI (Seismology, Geophysics)

S01e - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-3561

Point spread functions for earthquake source imaging: Connection with seismic interferometry

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Recently, various methods have been proposed and applied for earthquake source imaging, and theoretical relationships among the methods have been demonstrated. We follow-up with a theoretical study to better understand the meanings of earthquake source imaging. For imaging problems, the point spread function (PSF) is used to describe the degree of blurring and degradation in an obtained image of a target object as a response of an imaging system. In this study, we formulate PSFs for earthquake source imaging. By calculating the PSFs, we find that waveform source inversion methods remove the effect of the PSF and are free from artifacts. However, the other source imaging methods are affected by the PSF and suffer from the effect of blurring and degradation due to the restricted distribution of receivers. Consequently, careful treatment of the effect is necessary when using the source imaging methods other than waveform inversion. Moreover, the PSF for source imaging is found to have a connection with seismic interferometry with the help of the source-receiver reciprocity of Green’s functions. In particular, the PSF can be related to the Green’s function for cases in which receivers are distributed so as to completely surround the sources. Furthermore, the PSF acts as a low-pass filter. Given these considerations, the PSF is quite useful for understanding the physical meaning of earthquake source imaging.

IASPEI (Seismology, Geophysics)

S01e - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-3989

Teleseismic peak ground accelerations from the may 24, 2013 sea of Okhotsk deep earthquake

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The 2013 Sea of Okhotsk deep earthquake (M8.3), which was recorded by many global seismic stations with adequate coverage of azimuth and distance, provided an opportunity to understand the global characteristics of ground shaking. Peak ground accelerations (PGA) from the Sea of Okhotsk earthquake decreased with distance up to 120°. PGA values at distances between 40° and 85°, which are the target in the present study, are associated with vertical components of direct P waves, and the values are in a range from 0.0001 to 0.01 m/s. The variation with distance and the values are similar to those of the 1994 Bolivia earthquake (M8.3). The average decay with distance agrees with that of the P-wave amplitude predicted by the ray theory using lower-mantle attenuation in the range obtained previously by Hwang and Ritsema (2011) and PREM. Frequencies characterizing the PGA decay are between 0.8 and 1.8 Hz. Comparison with observations from deep earthquakes in the other regions suggests that the P-wave radiation pattern can affect the variations of PGA with distance by controlling the amplitude of P waves in the frequency range. Spatial variations in PGA can depend on the tectonic setting; large values of PGA are observed in stable continents and old seas, whereas small values are observed in tectonically active regions. Considering observations from other deep earthquakes in the Sea of Okhotsk, it is likely that PGA values have a positive correlation with shear velocity variations at depths of around 100–150 km below the stations.

IASPEI (Seismology, Geophysics)

S01e - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-4232

High-resolution, uitra low power, intergrated aftershock and microzonation system

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Rapid Aftershock Mobilization plays an essential role in the understanding of both focal mechanism and rupture propagation caused by strong earthquakes. A quick assessment of the data provides a unique opportunity to study the dynamics of the entire earthquake process in-situ. Aftershock study also provides practical information for local authorities n order to conduct the necessary actions for public safety in the area affected by the strong earthquake.

The 160-03 is a self-contained, fully integrated Aftershock System, model 160-03, providingsimple and quick deployment during aftershock emergency mobilization. The 160-03 has no external cables or peripheral equipment for command/control and operation in the field. The 160-03 contains three major components integrated in one case: a) 24-bit resolution state-of-the art low power ADC with CPU and Lid interconnect boards; b) power source; and c) three component 2 Hz sensors (two horizontals and one vertical), and built-in ±4g accelerometer.

The self-contained rechargeable battery pack provides power autonomy up to 7 days during data acquisition at 200 sps on continuous three weak motion and triggered three strong motion recording channels. For longer power autonomy, the 160-03 Aftershock System battery pack can be charged from an external source (solar power system). The data in the field is recorded to a built-in swappable USB flash drive. The 160-03 configuration is fixed based on a configuration file stored on the system, so no external command/control interface is required for parameter setup in the field. For visual control of the system performance in the field, the 160-03 has a built-in LED display which indicates the systems recording status as well as a hot swappable USB drive and battery status.

IASPEI (Seismology, Geophysics)

S01e - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-5087

Amplitudes of sP depth phase observed at small epicentral distances from offshore earthquakes in the northeastern Japan

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Travel times of sP phase have been widely used to improve depth accuracy of earthquakes for both far- and near-field observations. However, the amplitudes of sP phase has not been paid much attention probably because the amplitudes may depend on many parameters. Here we developed an automated technique to detect sP phase and measure its amplitude to search for future use of amplitude data. The method consists of the picking of possible arrival times for each station, screening data through depth relocation, and amplitude correction. The first step picks possible data of arrival times and amplitudes in the time windows that satisfy the criteria of polarization characteristics. The combined data from all stations are organized into several groups based on the relation between sP–P times and epicentral distance. The screening process selects the best group that gives the least travel time residuals from the event depth revised by sP–P times. Finally, the amplitudes are corrected for the dependence on epicentral distance. We applied the method to the band-pass filtered seismograms from offshore earthquakes of the northeastern Japan. The center frequency of filter is 1 Hz. The variation of relative amplitude on the focal sphere is partly consistent with that of SV wave expected from the CMT solution. The spatial distribution of amplitudes plotted at reflection points show complex pattern that suggest no significant correlation with the submarine topography. Thus the amplitude of sP phase probably reflects source radiation, together with some additional factors such as spatial heterogeneities of reflectivity. This result suggests potential use of sP amplitude to constrain the focal mechanisms of offshore earthquakes.

IASPEI (Seismology, Geophysics)

S01f - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-0375

Analysis of complexity in seismic time series

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At present seismic data sets obtained from earthquakes catalogs depending on the approach are considered in a wide range of models: from fully random to very ordered. The results of analysis depend on the mathematical formalism used by author. In practice the preferred approach is to approximate seismic data series as random (Poissonian) process to obtain time-independent assessment of seismic hazard. In reality seismic catalogs contain both independent and strongly correlated events due to complexity of earth system. To get rid of this nonrandom content (correlated events) real seismic time series undergo dangerous surgical operation – so called declustering. Usually such distortions of original processes taking place in complex systems complicates the task of understanding the underlying physics of earthquakes. Continuous seismic records (seismograms) contain besides data on significant separate events (earthquakes) also information on the relatively weak processes, such as seismic noise, dynamically triggered events (tremors) etc. These events are usually ignored in the standard seismic processing, though mentioned new nonlinear dynamics tools may reveal important fine details of the seismic process, related to the physics of seismic source. In case of seismic data sets of any origin (retrieved from earthquakes catalog or from characteristics of the continuous seismic record) need to be carefully investigated by a complete data analysis tools including traditional statistical approach as well as modern nonlinear tools revealing: long- and short range correlation, memory, scaling, recurrence features etc.

IASPEI (Seismology, Geophysics)

S01f - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-1017

Thin structure of GPS time series noise

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Traditional use of GPS time series consists in analysis of trends only and ignoring of random fluctuations which are considered as 'noise', which should be suppressed. Here we in contrary with this tradition pay attention to investigating thin structure of GPS noise which could be a source of important information about underlying geological structures and processes preparing geo-catastrophes. We investigated such properties of GPS noise as spectral index, multifractal singularity spectrum support width, generalized Hurst exponent, wavelet-based smoothness index, measure of non-stationary behavior. These statistics were estimated within moving time windows. For each time window a spatial maps of noise parameters could be created by calculating median values of noise characteristics from given number of nearest GPS stations to each grid node of the maps. The mean maps are estimated by averaging maps from each window within given range of dates. Using of principal components method allows take into account information from all 3 components of GPS time series.

The methods are illustrated by processing information from networks of stationary GPS stations in Japan (1203 stations) and West USA (2176 stations). It is shown that 1st principal component of GPS noise wavelet-based spectral indexes maps by information within time interval over 40 days of observation before the Tohoku mega-earthquake on March 11, 2011 (M = 9.0) clearly extracts the region of future seismic catastrophe by relatively high noise spectral index.

IASPEI (Seismology, Geophysics)

S01f - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-1106

Can the DD-relocated earthquake catalogue be used for the statistical parameters of an earthquake sequence? A case study

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Relocated earthquake catalogue by double difference (DD) algorithm, while significantly improving the location precision, suffers from the degeneration of catalogue completeness. One of the questions subject to discussion is whether such DD-relocated catalogue is really an improvement, or otherwise a drawback, when calculating the spatially dependent statistical parameters of seismcity. In such calculation, catalogue completeness is one of the key issues determining the quality of the result. Investigating this problem, we carried out a case study on the August 3, 2014, Ludian, Yunnan Province, southwest China, M_S6.5 earthquake sequence. Aftershocks within 40 days since the mainshock were analyzed using the routine catalogue provided by the Chinese national seismograph network and a DD-relocated catalogue. The Gutenberg-Richter b-value, as well as its spatial distribution, from both catalogues, were calculated and compared to each other. It was shown that the degeneration of catalogue completeness of the DD-relocated catalogue depends on the clustering property of the earthquakes. Degeneration of catalogue completeness mainly occurs at the margin of an earthquake cluster. Remarkably, different from the routine network catalogue, based on the DD-relocated catalogue, spatial distribution of b-values provides clues to the source properties of the earthquake.

IASPEI (Seismology, Geophysics)

S01f - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-1716

Natural Time analysis of seismic time series: A review of recent results

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Natural time analysis reveals novel dynamic features hidden in the time series of complex systems and enables the identification of the approach of a complex system to a critical point, thus being useful for predicting catastrophic events. Focusing on the case of seismicity, an order parameter (κ_1) has been defined in natural time which can be directly computed from seismic catalogs. For example, the Japan seismic catalog was analyzed in natural time by employing a sliding natural time window comprising a number of events that would occur in a few months. This is a crucial time scale since it corresponds to the average lead time of the observed Seismic Electric Signals (SES) activities that are low frequency ($\leq$1Hz) electric signals emitted when the stress reaches a critical value in the focal area and the system enters the critical stage before earthquake occurrence. The following results have been deduced:
First, the fluctuations of κ_1 of seismicity exhibit a clearly detectable minimum approximately at the time of the initiation of an SES activity. These two phenomena were shown to be also linked in space.
Second, the catalog was analyzed in natural time from 1 January 1984 to 11 March 2011 (the day of the Mw9.0 Tohoku earthquake). The fluctuations of κ_1 of seismicity were found to exhibit distinct minima a few months before all the shallow earthquakes of magnitude 7.6 or larger. The deepest minimum was observed before the Mw9.0 Tohoku earthquake accompanied by anomalous magnetic field variations mainly on the Z component, which reveals that a strong SES activity should have been simultaneously initiated. A spatial study of this minimum shows that it originates from an area lying within a few hundred kilometers from the epicenter.

IASPEI (Seismology, Geophysics)

S01f - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-1900

The mantle anisotropy obtained from shear-wave splitting in the region of 1891 Nobi earthquake

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The 1891 Nobi earthquake was one of the largest inland earthquakes in Japan. We researched shear-wave splitting to obtain seismic image around the 1891 Nobi earthquake area. The deep earthquakes occurred from 2009 to 2014 were used. The seismic stations of Hi-net and the temporary seismic network operated by our group were used.

The results suggest very interesting and remarkable pattern of the polarization directions. The polarization directions of NE-SW and E-W are obtained in the northeast and east of the 1891 Nobi earthquake area, respectively. However, the polarization directions around the 1891 Nobi earthquake are NW-SE. The large time-lag values, which are larger than 0.5 sec, are observed at many seismic stations. The value is much larger than the maximum crustal anisotropy (~0.1 sec) observed in this area. We consider that the observed shear-wave splitting is caused by the mantle anisotropy.

The polarization direction with E-W at the eastern part of the research area and the polarization direction with NE-SW are consistent with the results of previous studies. The polarization directions can be explained by the preferred orientation of the olivine crystal cause by the mantle flow relating to the subducting Pacific and Philippine Sea plates. However, the polarization direction with NW-SE is not consistent with both of the directions of the subducting oceanic plates. Then, we suppose that the some heterogeneous structure might cause the anisotropic region in the mantle. The shear-wave splitting caused by the heterogeneous structure, which was related to the rising magma in the mantle wedge, was reported. The observed shear-wave splitting might be related to the heterogeneous structure caused by the fluid or magma.

IASPEI (Seismology, Geophysics)

S01f - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

IUGG-2305

Possibility of remote triggering of the 2014 Mw7.9 Rat Islands earthquake examined by an integrated seismicity model

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Seismic waves propagating from large earthquakes cause global transient stress changes capable of triggering other earthquakes at great distances. The study of such remote and dynamic triggering phenomena provides a better understanding of the mechanisms that generate earthquakes. I introduce an integrated seismicity model to stochastically evaluate the time intervals of consecutive earthquakes at global scales, making it possible to detect a pair of earthquakes possibly related to each other. The model includes seismicity in non-overlapping areas and comprehensively explains the seismicity on the basis of point process models, which include the stationary Poisson model, the aftershock decay model following Omori-Utsu's law, and/or the epidemic-type aftershock sequence (ETAS) model. I examine the possibility of triggering of the 2014 Mw7.9 Rat Islands earthquake that occurred within one hour after the Mw6.7 Kermadec earthquake that located about 9,000 km away. The estimated probability that the time interval is shorter than that between these events is not more than 0.01% when I assume there is no relationship between seismicityin these regions. The Rat Islands event occurred during the passage of seismic surface waves propagating from the Kermadec event, which produced small stress changes varying within at most about 10 Pa at the hypocenter of the Rat Islands event. These results suggest that a causal relationship may exist between these events, where the surface waves from the Kermadec event probably caused a reduction in the fault's strength by cyclic fatigue and eventually triggered its failure during their passage.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-530

Stratigraphy and geoacoustic model of the late Quaternary shelf sediments in the South Sea, Korea

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Chirp acoustic subbottom profiling and sparker seismic survey have been carried out to understand the stratigraphy of the South Sea continental shelf of Korea. Sediment samples were also collected by eight piston cores to investigate the depositional environment as well as sediment characteristics of late Quaternary deposits in the study area. A couple of deep drill core data were utilized to help understand the deeper sedimentary sequence. The combination of the deep drill cores and high-resolution seismic profiles result in classification of the study area for three depositional sequences.

The late Quaternary deposits in the study area can be divided into seven sedimentary units bounded by an erosional surface and internal seismic reflectors. Sea-level change played the important role for forming the units. The lowermost sequence D1 is characterized by subparallel and progradational reflection patterns representing regressive estuarine/deltaic deposits (unit S1 and S2). DII is composed of transgressive incised channel fill (unit S3), transgressive sand sheet (unit S4), and transgressive sand ridges (unit S5), inner shelf transgressive sand sheet (unit S6). DIII is the Holocene mud deposits (unit S7). The highstand systems tract (unit S7) overlying the maximum flooding surface (MFS) is the recent mud deposits. The Holocene mud deposits called CSSM can be lined into two different provinces by the internal reflectors and sediment physical properties. The possible sources of the mud are Seomjin River discharge and transported from the southeastern part of

the Yellow Sea. The boundary lies in the southeast of Geumo Island. Geoacoustic properties, clay mineral distribution and satellite images of the study area also support the drawing line.

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IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-531

Establishment of seismic network in the Taiwan mountain area

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Consisting of more than 800 stations, a strong motion network (Taiwan Strong Motion Instrumentation Program, TSMIP) has widely deployed in the Taiwan area by the Central Weather Bureau (CWB) since 1991. The majority of seismic stations are placed at the plain area; some stations are placed at the mountain area. This area, with peaks up to 4000 m, covers an area of 2/3 of the entire Taiwan Island which was the region that lack of earthquake records over past many years. In 2006, Taiwan's Institute of Earth Sciences (IES) of Academia Sinica has encouraged to extend the seismic observations to the mountain area. With the supports from the CWB, 16 seismic stations have installed in 2006 and increases to 80 stations in 2013. The progressive development towards a better distributed of seismic network has greatly contributed to the improvement of earthquake detection and monitoring in the mountain area. In this report, we describe works of our installation and data collection of the mountain seismic network. Some representative records from the recently moderate-sized inland earthquakes are shown here. Seismic data from the mountain area and TSMIP will be integrated to study the path effects and site effects from different seismogenic zones to the metropolitan area and improve our understanding of the seismic sources located in the mountain area.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-532

Using the Empirical mode decomposition method for seismogram interpretation

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All the earthquakes are transient and nonstationary. For lack of alternatives, in seismology as well as earthquake engineering, most data are still processed by using the Fourier analysis. The most difficulties in the Fourier spectral analysis are associated with nonlinearity and non-stationary nature of the data. Such methods cannot reveal the detailed information in the dispersion properties, the wave form deformation, and the energy-frequency distribution. In this paper, a technique based on the time-domain Empirical Mode Decomposition has been explained, which enables us to analyze both short-term information and long-term structures in seismic waves. It provides insight into long term memory and local time behavior of seismic signals. Oscillation modes of seismic waves generated by different types of source (earthquakes and explosions) are compared to each other, relationships between each group of the same data and differences between different data are obtained based on the produced Intrinsic Mode Functions (IMFs). With respect to the advanced methods such as discrete stochastic non-Markov process it has been shown that this technique gives better identification. Plotting the maximum frequency of different IMFs via position of them, gives an effective identification tool. In this study first the technique is explained and then the obtained results are illustrated and discussed.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-533

Rapid concurrent epcentre and hypocentre localisation for tracking earthquakes in real-time upon their initial detection: a review

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This paper reviews several papers and two reports that incorporate work done leading to the development of an algorithm which rapidly evolves a concurrent localization of the Epicenter and Hypocenter of an Earthquake in real-time. This algorithm is conceived as an “interpolative tabular scan” in which the tables are generated by point-to-point ray tracers, using a set of Earth velocity models. Both the tracers and the velocity models are chosen parametric to the process.

The tables take the form of matrices in a 2-space dimensioned by depth (of the emission) and colatitude (of surface arrival points). The pole for the set of colatitudes is oriented above the source of the target Earthquake.

This algorithm defines a physical system of a network of stations any of which, on detecting a P-wave onset, would communicate a timing to a central facility. As these reports accumulate the concurrent localizations of Epi- & Hypocenters for the event can evolve as the set of timings to be processed enlarges. It can be possible to eliminate “unassociated” data from any set of onset timings by applying Chauvenet’s criterion for outlier rejection. The algorithm also supplies a set of take-off angles corresponding to each station identified as a component in the set leading to a particular localization.

On a 3.2 GHz processor the timings for groups of 5 to 8 stations start at ca. 0.7 s/station and increase to ca. 1.3 s/station for groups of up to 30 stations, depending on computer background activity.

This algorithm is seen as a front-end process for an Earthquake Early Warning (EEW) system which would allow more rigorous processes to be initiated once these basic source localizations have been established. Tsunami alerts would be considered if a maritime localization was found.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-534

Analysis and research on microseismic signal in continental seismological observation

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In continental seismological observation, microseism is very active. After the analysis on more than a year of continuous waveform data in the Eurasian continent seismological observation (mainly Chinese observation), the results show that: there are many different kinds of the microseism signals in seismological observation, and the amplitude of some microseism even is equivalent to small magnitude earthquake. In addition to earth tide and the seismic background noise, there are many unknown cause signals. The characteristic differences between various signals are very large. In this article, we analyze and summarize the duration of these signals, the spectral characteristics, variation characteristics and distribution characteristics of observation. To focus on analysis on mutual relations among the positioning of signal source, the signal and large-scale meteorological movement, the ocean storms, and the tectonic environment. This article explains types of the some signal source, and summarizes research results and progress in recent years.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-535

On revision of Bakanas earthquake parameters of 1979 (kazakhstan), ?w=5.7 basing on digitized analogue seismograms

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Bakanas earthquake occurred on September 25, 1979 with intensity 7 in the epicenter, Mw=5.7 surprised seismologists for several reasons.

1. Location of earthquake in the region considered as aseismic, where there were no earthquakes with M>4. In 1979 the epicenter coordinates were determined uncertainly as records of stations were clipped. Data which became available recently from the IDC changed slightly the epicenter location, it shifted eastward on 0,1 degree.

2. The focus depth determined in 1979 by minimization of travel time residuals was equal to 40 km. The specialists distrusted this value as most earthquakes of Northern Tien Shan have depth less than 25 km. However, according to data of the IDC that determined depth phases pP and sS, the depth is equal to 46 km (ISC) and 40,7 km (EHB).

3. Despite magnitude close to 6, the earthquake was not accompanied either by forshocks, or aftershocks.

4. Disagreement of focal mechanism (MO) and CMT (Centroid-moment Tensor), although for other Kazakhstan earthquakes the solutions are usually quite similar.

This set of abnormal signs confirms unusual nature of Bakanas earthquake. These circumstances stipulated new investigation of its focus, more than 30 years after the earthquake.

Analogue seismograms of lowered sensitivity channels of SK instruments were digitized. It was determined that the earthquake origin had two shocks in 11 seconds interval. Energy characteristics were evaluated for each of two shocks. Disagreement of MO and CMT is explained. The recent results of the region tectonics are provided.

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Focal mechanisms as criterion for explosions discrimination

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First motion of P-wave and focal mechanism used for standard filtration of phenomena. The basis of this criteria application for seismic events nature discrimination is in known character of compression and longitudinal waves distribution from different sources. Compression and longitudinal waves of earthquakes have quadrant distribution, force source is double couple force. Explosion is a source of all-round expansion, positive shifts should be observed in first arrivals of P- waves in all directions from an epicenter.

However, our practical observations showed that it is not always possible to discriminate an explosion using these criteria. In some cases on the seismograms of the same explosion obtained in different azimuths from an epicenter both positive and negative shifts were observed in first motions. For some explosions focal mechanisms were determined using standard techniques. Parameters of focal mechanisms received for explosions were typical for earthquakes focus mechanisms of the region.

The present work is aimed at revealing explosions which can be considered as exclusions according to their first motions in P- waves and focal mechanism parameters. We have focused on different explosions types: nuclear, calibration, quarry.

Thus, it is not always possible to identify definitely an explosion using such criteria as “first motion of P-wave” and “focal mechanism”. Abnormal cases by these criteria were revealed among explosions of different types: nuclear, calibration, quarry. Focal mechanisms solutions obtained for explosions, as rule, are similar to earthquakes mechanisms in relevant tectonic structures.

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Location of seismic events in the Eastern Barents Sea region

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The eastern part of the Barents Sea, including the archipelago of Novaya Zemlya, is considered to be relatively aseismic. Since 1985, fewer than 20 earthquakes have been observed in the area, spanning the magnitude range 2 and above. Only the two largest events could be observed and located using observations at teleseismic distances (in 1986, ISC m_b 4.8; and in 2010, ISC m_b 4.7), whereas the other events were located primarily using observations at regional and far-regional distances at stations generally to the east of the events.

On 4 March 2014, a magnitude 3 event occurred on the central part of Novaya Zemlya. In addition to the observations at the sensitive arrays in northern Norway (ARCES), Spitsbergen (SPITS) and Apatity (APA), Pn- and Sn-arrivals from this event could this time also be well observed at the new station ZFI2 on Franz-Joseph Land, at a distance of about 730 km to the north of the event.

In this study we investigate the sensitivity of using different network configurations and regional velocity models for locating the 4 March 2014 event. Initial results suggest a very strong dependency of the upper mantle S-wave velocity model.

This research is carried out within the cooperative international Russian-Norwegian projects of the Russian Foundation for Basic Research ?14-05-93080 and the Research Council of Norway ?233973 «Seismological research related to geophysical processes in the European Arctic»

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Signal enhancement of OBS data using wavefield separation in Mahanadi offshore basin, India

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Ocean bottom seismometers (OBS) are the instruments stationed on ocean floor that have the ability to record entire wavefield using 3 component (Z,X,Y) geophone and one hydrophone (P). The data obtained by OBS instruments is often contaminated by free surface multiples that interfere with the recorded wavefield and need to be removed for further processing/modeling. The geophone record is direction dependent, while the hydrophone record is direction independent. This discerning aspect can be utilized to eliminate the free surface multiples by simple summation of the P and Z components (PZ). However, the PZ summation is very effective in removing all the receiver side multiples (ghost), but not very effective in removing the source side multiples. To overcome this shortcoming, wave field separation has to be carried out, involving separation of the wavefield (Z component) into up and down going fields. The deconvolution of the upgoing field with the downgoing field is then carried out resulting in the multiple free (source and receiver) wave field (PP reflectivity). Similar approach can be extended to extract the PS converted wavefield by deconvolving the radial (X) component of OBS data with the downgoing wavefield. The technique enhances the signal to noise ratio (SNR) to a significant level and is applied to the OBS data acquired in the Mahanadi Basin, eastern Indian offshore. A considerable increase in SNR is noticed in the PP reflectivity and a noticeable increase in resolution is observed in the PS reflectivity.

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Similar earthquakes extracted from the Japanese seismic network

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Observations in Japan suggest that many sequences of similar earthquakes which occurred in the subducting plates are caused by repeating slips of small patches surrounded by aseismic slip areas at the plate boundary. In this study, I investigate the space-time characteristics of similar earthquakes occurred in Japan and world by calculating cross-correlation coefficients of band-pass filtered seismograms. I analyzed waveform data observed in the Japanese seismic network for about 13 years from 2002. As a result, I found many sequences of similar earthquakes in the subducting plate boundaries of Japan, Sumatra and Tonga. The slip-rates estimated from these sequences by applying the scalar moment - slip relation proposed by Nadeau and Johnson (1998) had indicated the space-time changes of inter-plate aseismic slip. Slip-rates with over 10 cm/yr correspond to the post-seismic slip after the 2004 Sumatra earthquake and the 2011 Tohoku earthquake, and the fast relative plate motion in the Tonga subduction zone. I believe that I am likely to detect more similar earthquakes by extending analysis periods in the area where they were not found in this analysis. The database of similar earthquakes enables the comparison of the inter-plate aseismic slips of various subduction zones of the world. Furthermore they will be useful for extracting information on space-time changes of seismic velocity structures beneath the Japanese Islands.

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S01p-540

Mathematical modelling of the wave fields in anisotropic media and determining the earthquake source parameters

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The modification to the matrix method of construction of wavefield on the free surface of an anisotropic medium is presented. Wave propagation in multilayer media requires that displacement and stress vectors be continuous everywhere, including the interfaces. Seismologists have been able to invert the rupture process of a number of earthquakes, and many of the features predicted by simple dynamic source models have been quantified and observed. Thus, the methods, approaches, algorithms for the propagation of seismic waves and results of direct and inverse dynamic problems of seismology proposed and developed by the author can be successfully used in the study of the seismic regions and effective implementation in the construction of the earthquake source mechanism which is crucial for seismic regions of the Ukraine.

The analytical-numerical approaches have been developed, based on matrix method and its modification, for determining the source time function from spectra of seismic records. The trial and error method for determining the angles of orientation of fault plane and earthquake mechanism has been proposed. The advantage of the trial and error method is the possibility of using it for determining the focal mechanism in the case of a small number of seismic stations which record this event.

The algorithms proposed have been tested on synthetic and real data. The analytical-numerical and trial and error approaches have been applied for determining the source parameters of earthquakes in seismically active region of Eastern Carpathian. It has been demonstrated that the result is most reliable for epicentral distances lesser than 75 km. A comparative analysis has been conducted between the earthquake mechanisms determined using trial and error and graphic methods.

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S01p-541

Complex networks for seismicity analysis and hazard assessment of large earthquakes: the 2009 L'Aquila Earthquake as a Case study

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Seismicity is a 3-D extremely complex process evolving in the heterogeneous space, time and size domains. Over the last years, the underlying statistical properties of seismicity have attracted increasingly great interest enhancing our understanding of the complex physical mechanisms that cause earthquakes. Key statistical network measures could be potentially useful for the short-term hazard assessment of the occurrence of mainshocks in the presence of foreshocks. Our study is focused on the case of the L'Aquila (Italy) mainshock () of 6th April 2009. Using successive connections between events acquired from the earthquake catalogue of INGV, we provide evidence that global network measures (such as the average clustering coefficient, efficiency, small-world index, critical exponent of the degree distribution) and local ones (betweenness centrality,) can be exploited for forecasting purposes both in time and space. Our results reveal simultaneous steep changes of the topological measures about 10 days before the mainshock and a nucleation of the around the location of the epicenter about two months before the mainshock. The results of the analysis are robust even when considering either large or off-centered the main event space-windows. The proposed approach holds promising regarding the identification of spatio-temporal patterns related to the underlying seismicity and thus could be potentially serve as alternative and/or complementary to well-established traditional statistical methods for short-term, time-dependent hazard assessment of earthquakes.

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S01p-542

Seismic waves in layered media and the inversion for source parameters

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This paper is organized as follows. After a discussion of the differential equations for wave propagation in the horizontally stratified medium and of the initial and boundary conditions, we derive the displacements on the free surface of the layered medium for plane waves when a point source is located on the s-th imaginary boundary at the depth (physical parameters of the layers s and (s+1) are put to be identical). Then, the source will be represented as a single force of arbitrary orientation and a general moment tensor point source. Further, “a primary field” for a point source will be introduced. Method for the solution of the direct seismic problem is considered based on the matrix method of Thomson-Haskell. The tensor represents a superposition of three single couples without moment along the x, y, z-axes and three double couples in xy, xz, yz-planes. Further, we give the results for the field of displacements on the free surface.

The results of this direct problem we use in the inversion of source parameters The inverse method relies on inverting for components of the moment tensor and a determination of an earthquake source-time function.

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S01p-543

Are there attractors in seismic time series?

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Seismic time series documented as seismic catalogs are objects of detailed statistical analysis, which show that catalogs contain both independent and correlated events (clusters). It is accepted that it is important to pick out independent events for a practical application in (time-independent) seismic hazard assessment. At the same time analysis of the correlated events' pattern is very important for understanding dynamics of seismic process. In some earlier works (Goltz, 1997; Matcharashvili et al, 2000) it is shown that at least one component of catalogs considered as a point process, namely, interevent or waiting time series has a low fractal dimension, which means that catalogs contain some hidden nonlinear structures, which however cannot be considered as attractors. Last years there are publications on revealing attractors in seismic time series, which means that they can be represented by deterministic chaos model (Sobolev, 2011). So, it seems interesting to study, what methodology should be applied to seismic time series (STS) in order to reveal possible attractor structures. There are two main approaches to the problem: i. events in STS are considered individually; ii. the number of events in STS in some time window or a seismic rate is calculated, which is widely used as a proxy of the strain rate.

The study considers how the spatio-temporal parameters of seismic rate calculations affects the nonlinear structures (phase plots) before and after strongest Caucasian earthquakes Spitak (1988) and (Racha, 1991) as well as in aseismic areas. The seismic phase portraits are constructed for several time windows, different epicentral distances and different magnitude thresholds.

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Non-random component of the spatial-temporal earthquake distribution between the Northern part and the Southern part of the Pacific

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The Earth's seismic activity demonstrates distinct roughness (nonuniformity) in time. It was noted also that peaks of the events in the Northern hemisphere and in the Southern hemisphere do not coincide in time. We are checking existence of the nonrandom component in the sequence of the earthquakes (with M≥7 for the period from 1890 to 2013). A nonparametric run test was used for testing of hypothesis about if the sequence of the events contains nonrandom component. All events were related to the time axis according to their origin time.

The statistical value Z=f(n1,n2, R) is calculated on the basis of three parameters (n1 and n2 - the number of events occurred in Northern and in the Southern hemisphere, and R is number of the series (set of consecutive events of one type). The confidence interval for α=1% is defined by condition |z|<2.58. If |z|³2.58 then given sample contains non-random component. Using the run test for events with M≥7, with M>=7.5 and M> = 8 we obtained that the Zn values for all magnitude ranges exceeded |2.58| in several times, thus a periodic transfer of the seismic activity between the Northern Hemisphere and the Southern Hemispheres is confirmed.

The digital model (superposition of the random processes and the periodic process) was proposed. The statistical validity of the periodic component according to run test depends on: the frequency of the periodic function, the duration of the observation period, and the probability of random component occurrence as function and some other parameters.

The digital model enables to comprehend some particular features of the observation data.

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S01p-545

Recent seismicity Crimea

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Some aspects of the seismicity of the Crimean-Black Sea region on the basis of catalogs and bulletins earthquakes between 1970 and 2012 are discussed. Obtained rescheduling in recurrence of earthquakes from year to year and seasonal cycle of energy released during earthquakes. Total catalog of earthquakes in the Crimea during this period contains about 2140 events with magnitudes from -1.5 to 5.5, bulletins contain information about the parishes of longitudinal and transverse waves at seismic stations around 1000 earthquakes. On the basis of a new approach to the determination of the position of earthquake hypocenters redefined the coordinates of all the events for which data are presented in the bulletins of the Crimean Black Sea region. Of greatest interest is the spatial distribution of hypocenters Crimean earthquakes. Firstly, the majority of earthquake hypocenters lie deeper 12 km, which corresponds to twelve kilometer border in the mountainous part of the Crimea and almost no hearths which would go to the surface. Second, the distribution of earthquake hypocenters is close to the conical shape with the apex near Yalta, Alushta and earthquake sources reach a depth of 250 km. This distribution of foci significantly changes geodynamic picture of the region.

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Automatic analysis of joint data from seismo-acoustic network and infrasonic arrays in Israel

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We explore a joined analysis of seismic and infrasonic signals for improved automatic monitoring of small local/regional events, such as construction and quarry blasts, military chemical explosions, sonic booms, etc. using collocated seismic and infrasonic networks recently build in Israel (ISIN) in the frame of the project sponsored by the Bi-national USA-Israel Science Foundation (BSF). The general target is to create an automatic system, which will provide detection, location and identification of explosions in real-time or close-to-real time manner. At the moment the network comprises 15 stations hosting a microphone and seismometer (or accelerometer), operated by the Geophysical Institute of Israel (GII), plus two infrasonic arrays, operated by the National Data Center, Soreq: IOB in the South (Negev desert) and IMA in the North of Israel (Upper Galilee),collocated with the IMS seismic array MMAI. For automatic event detection and phase picking we tested the new recursive picker, based on Statistically optimal detector algorithm and a new robust location techniques for joint seismic and infrasonic source detection and location and compared to the InfraMonitor procedure based on the Bayesian Infrasonic Source Localization (BISL) method. The semi-empirical model-based prior information, was utilized for array+network configuration and applied to the ground-truth events for the best location results.

IASPEI (Seismology, Geophysics)

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S01p-548

Initial report about the Middle-Lower Yangtze Metallogenic Belt seismic experiment in East China

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From May 2012, China University of Geosciences (Beijing) began to deploy a temporary broadband seismic network that was designed to explore the crustal and upper mantle structure of the Middle-Lower Yangtze Metallogenic Belt (MLYMB) and its adjacent regions with an average station spacing of ~50 km. The first phase of this experiment, which consists of 20 CMG-3ESPC broadband seismometers, operated from May 2012 to June 2014. Since June 2014 the second phase began to operate, which consists of 15 CMG-3ESPCD and 10 NANO broadband seismometers. Given the importance of data collected in this experiment to, and the timely nature of, the study of the deep geodynamic process and magmatic activity mechanism of the MLYMB, this initial report presents the experiment setting, initial data collected, and results of preliminary data analysis in the spirit of promoting data exchange and collaborative study of the MLYMB. This project is supported by the Ministry of Land and Resources of China?under the Project SinoProbe-03, the National Science Foundation of China 41374057 and 41474045,and the Program for New Century Excellent Talents in University (NCET).

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The 19 October 2013 M=6.3 Loreto region, Gulf of California, Mexico, earthquake

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We study the source characteristics and S-wave attenuation of the 19 October 2013 (M=6.3) earthquake and eight aftershocks located 89 km east of Loreto, Baja California Sur, Mexico. We also analyzed records from a foreshock with magnitude 4.0 that occurred 37 hours before the main shock. The epicenters of this sequence are located in the south-central region of the Gulf of California along the Farallón fault. This is one of the most active regions of the Gulf of California, where most of the bigger earthquakes are strike-slip events. Based on the distribution of the aftershocks, the rupture propagated northwest with a rupture length of approximately 30 km. We calculated 3-component S-wave spectra from ten events recorded by eleven stations of the Broadband Seismological Network of the Gulf of California (RESBAN). These stations are located around the gulf and provide a good azimuthal coverage. The spectral records were corrected for site effects, estimated calculating average spectral ratios between horizontal and vertical components (HVSR method). The site corrected spectra was then inverted to determine the source functions and to estimate the attenuation quality factor Q. We will present the results of this spectral inversion.

IASPEI (Seismology, Geophysics)

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S01p-550

EARTHQUAKE SEQUENCE IN EAST VRANCEA CRUSTAL REGION (ROMANIA), NOVEMBER 2014 - JANUARY 2015: SOURCE CHARACTERISTICS AND SEISMOTECTONICS

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The goal of the paper is to investigate the crustal earthquake sequence generated in the East Vrancea crustal zone at the end of 2014 (22 November 2014) which is still in progress at present (January 2015). The main shock, occurred on 22 November 2014, 19:14 (45.86^{0}N, 27.16^{0}E, h = 39 km, M_L = 5.7), is the greatest instrumentally recorded earthquake produced in this region. The aftershocks are unusually small for the sequences characterizing the Vrancea foredeep area (around 200 events with magnitude below 2). The largest aftershocks occurred until 26 January 2015 were recorded on 7 December 15 (M_L = 4.4) and 19 January 2015 (M_L = 3.8). Seismic source properties are determined using multiple approaches: empirical Green's functions (EGF) deconvolution, spectral ratios technique and acceleration spectra analysis. At the same time we applied inversion techniques to retrieve the moment tensor solution for the largest shocks. For EGF and spectral ratios applications, we associated to the main event many co-located aftershocks ($2.0 \leq M_L \leq 4.4$), selected according to the requirements for empirical Green's functions. The source parameters are estimated as mean values for all the available earthquake pairs. Source scaling properties and focal mechanism are investigated and discussed in terms of the regional seismotectonics and comparatively with the source scaling relationships for the Vrancea intermediate-depth earthquakes.

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Morlet Wavelet Analysis of Earthquakes in the Taipei Metropolitan Area

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$M_L \geq 3$ earthquakes (M_L=local magnitude) that occurred in the Taipei Metropolitan Area from 1973–2013 are selected to study the dominant seismicity period of this area. The epicentral distribution and temporal sequences of earthquake magnitudes are simply described. These earthquakes can be divided into two groups: one for events shallower than 40 km and one for events deeper than 60 km. Shallow earthquakes are located mainly in the 0–10 km depth range north of 25.1°N, and down to 35 km for those south of 25.1°N. Deep events are located in the subduction zone, with a dip angle of about 70°. The Morlet wavelet technique is applied to analyze the dominant periods of temporal variations in numbers of monthly earthquakes in the shallow and deep ranges for three magnitude ranges, i.e., $M_L \geq 3$, $M_L \geq 4$, and $M_L \geq 5$. The results show that for shallow earthquakes the dominant periods are 15.4, 30.8, 66.1, and 132.2 months when $M_L \geq 3$ and 30.8 months when $M_L \geq 4$; while for deep earthquakes, the dominant periods are 16.5 and 141.7 months when $M_L \geq 3$ and 141.7 months when $M_L \geq 4$. The dominant period cannot be obtained for both shallow and deep $M_L \geq 5$ earthquakes.

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"Seismotectonics of southeast of Iran subduction zone, with emphasis on the 2013 earthquake in Sistan"

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Iran is located in the middle-east region, along the Alpine- Himalayan active mountain belt. Continental convergence between Arabia and Eurasia plates caused seismic deformation in Iran. As a result of the deformation associated with the collision several tectonic features were formed. Active subduction of the Arabia plate beneath the continental Eurasia plate, which converges at a rate of approximately 20 millimeters per year, dominates the regional tectonics in southeast of Iran. Although this subduction zone has a relatively slow convergence rate, it has produced large devastating earthquakes and tsunamis. On April 18, 2013, an earthquake with a magnitude 7.5 occurred in Sistan region. It was widely felt in Iran, Afghanistan, Bahrain, India, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia and United Arab Emirates. It was initiated as a result of normal faulting at an intermediate depth in the Arabian plate lithosphere, approximately 90 km beneath the Earth's surface, and propagated in a unilateral manner. the size of the main fault was about 70km in strike direction and 36 km in dip direction. In this study, in order to estimate source parameters and rupture characteristics of the earthquake, the Empirical Green Function method was used for strong ground motion simulation. The duration of rupture was more than 30 s. Strike, dip and rake of causative fault were determined as 85, 52 and -70 degrees, respectively. The stress drop was calculated as 84 bar.

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S01p-553

Measurement of anomalous radon gas emanation across the Yammouneh fault in Southern Lebanon: A possible approach to earthquake prediction

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Measurement of anomalous radon gas emanation across the Yammouneh fault in Southern Lebanon: A possible approach to earthquake prediction

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Abstract

The Yammouneh fault in Lebanon is a segment of the Dead Sea Transform Fault(DSTF). Measurements of radon gas exhalation rates across the southern segment of the Fault in South Lebanon were performed. Anomalous variable temporal increase and drop of radon concentration and exhalation rate were measured and correlated with stress/strain tectonic activity and stress-drops accross the studied fault segment boundary. The observed drop of radon intensity are correlated with several earthquakes, whose epicenters are located in the region of Tiberias Lake in Northern Israel-Palestine. The results of the measurements indicate that the lag time of the occurrence of earthquakes was on the order of a few weeks. The homogeneity of the terrain in the study area is a necessary condition for obtaining a reliable interpretation of the measured data. Longer time periods of measurements are recommended.

Keywords: Radon exhalation, earthquakes, stress/strain, CR-39, Lebanon.

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IASPEI (Seismology, Geophysics)

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Azimuth verification of the MeSO-net accelerographs ~towards the imaging of ground motions in the Tokyo metropolitan area ~

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In the Tokyo metropolitan area of Japan, large plate boundary earthquakes repeatedly occurred with intervals ranging from 200 to 400 years in the case of M 8 class, and with an interval of approximately 27.5 years in the case of M 7 class. Rapid prediction of damages on constructions due to such a large earthquake is important to quickly decide the priority order in recovery actions without waiting for on-site reports. Such a rapid prediction system requires an image of ground motion in the target area as an input, which is to be estimated from seismograms of dense seismological observation networks. A dense seismic array “MeSO-net” (Metropolitan Seismic Observation network), in which 296 accelerometers are installed with several kilometer intervals, was established in 2007 for the purpose of the disaster mitigation for forthcoming large earthquakes. Whether the actual azimuths of MeSO-net seismometers newly installed after 2009 were really in the magnetic north or not have not been verified yet, while the azimuths of three of the seismometers installed before 2008 were already confirmed to be in the opposite direction. Since such obvious errors in the azimuths badly affect subsequent data processing, we evaluate the azimuths of all seismometers based on the cross-correlation with seismograms recorded at nearby Hi-net tiltmeters and F-net broadband seismometers. Our result suggest that the northward components at more than 80 % of stations are determined to be within 10 degrees from the magnetic north, while those at the three stations are reconfirmed to rotate more than 90 degrees as the previous study pointed out.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-555

Casual seismic noise and its influence on the detection efficiency of earthquakes of small magnitude – case study in Hungary

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One of the most important earthquakes of the past 25 years in Hungary occurred on the 29th January, 2011 in the northern side of Vértes Hills (Hungary). The M_L=4.5 main shock has been followed by more than 400 aftershocks. The CSKK seismic station has been operating in the middle of this area. Half of the registered earthquakes at CSKK station had a magnitude value less than M_L=0.2. The number of registered small earthquakes shows a diurnal variation: more M_L<0.2 events were detected during the night. This variation is due to the higher level of cultural noise in the area during the day which lowers the detection efficiency for small earthquakes.

Seismic noise is an unwanted component of signals of ground movements recorded by seismometers from the point of view of reliable detection, identification, and analysis of earthquakes. Our aim was to compare different noise sources, and look for those the activity of which can cover small (M_L ~= 0.1) earthquakes occurring within a range of several kilometers from CSKK station.

We have studied several environmental events which are possible sources of seismic noise. The set of examined processes includes natural phenomena (e.g. wind, lightning) as well as various human activities (traffic including a lorry, a tractor as well as horse and carriage; working with a lawnmower; children swinging). The specific noise pattern generated by lightning in CSKK seismic records has been examined in details. This noise pattern consists in a sharp spike and a longer lasting disturbance that followed the spike after a gap of several seconds. The speed of later arriving signal peaks was almost the same as the speed of sonic waves in air.

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S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-556

Attenuation of high-frequency body waves in the crust of the Central External Dinarides

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The Central External Dinarides are known as a tectonically complex region of moderate seismicity where several strong earthquakes occurred in the last century. In order to gain insight into the attenuation of seismic waves in the area, the extended coda-normalization method was applied to band-pass filtered seismograms of local earthquakes recorded at seven seismological broadband stations. Obtained results indicate strong attenuation of direct body waves: $Q_{0,P} = Q_P$ (1 Hz) is found between 21 and 120 and $Q_{0,S} = Q_S$ (1 Hz) is between 46 and 113, whereas the exponent n in the power law of frequency dependence of the quality factor is found in the range of 0.63–1.52 and 0.65–0.97 for n_P and n_S, respectively. P-waves are on the average attenuated more than S-waves. The three island stations (DUGI, ZIRJ, HVAR) are distinguished by the strong low-frequency P-wave attenuation and more pronounced frequency dependence of the Q_P-factor ($Q_{0,S}/Q_{0,P} > 1.7$, $Q_{0,P} < 60$, $n_P > n_S$). The remaining four inland stations (UDBI, MORI, KIJV, CACV) all exhibit similar qualitative attenuation properties for P- and S-waves (n_P and n_S are almost equal 1; $Q_{0,S}$ and $Q_{0,P}$ are almost equal), although individual values of the Q-factors vary notably within this group. Low-frequency attenuation of direct S-waves in the crust is stronger than mean attenuation of scattered coda waves in the lithosphere, especially for long coda lapse-times. The results are also qualitatively in agreement with the thermal regime in the area.

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S01p-557

New sensor for monitoring seismic rotational ground displacement.

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Physical principles and technical features of the newly designed ring-shaped sensor for recording rotational seismic displacement and simultaneous compensation of translational movements is introduced. Sensor's functional characteristics, such as its sensitivity, frequency work-range, etc., are demonstrated by the results of sensor's testing.

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S01p-558

Seismic activity near the Mt. Hotaka in the Hida mountain range, central Japan, detected by the matched filter method

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Seismic activity near the Mt. Hotaka in the Hida mountain range, central Japan was analyzed by using the Matched Filter Method (MFM). This seismic activity started in April 2013 and most intense activity occurred in October 2013. The largest event took place on October 8, 2013 at 19:28 (JST) whose magnitude was 3.9 (Japan Meteorological Agency, JMA). Epicentral area extends about 4 km in EW direction with 1 km in NS direction at the eastern frank of the Mt. Hotaka. Originally, the MFM is a technique only for detecting earthquakes. However, in this analysis, we implemented MFM as an automatic hypocenter determination system that enables to locate earthquakes one by one. We installed about thirty (30) template earthquakes in the target region and more than 3,000 events were detected and about 800 earthquakes were located in the time period from April 2013 to October 2013. Number of located events in the same time period are about one and half times of those in JMA catalogue, which is the official catalogue in Japan. Comparison with manually inspected results indicates that location errors by MFM system is within a couple of kilometers. Although we understand manually inspected catalogue data is essential to evaluate seismic activity, we suppose MFM is one of the powerful tools to analyze the swarm activity automatically that concentrated in a small area such like this case or around volcanoes.

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S01p-559

A preliminary catalog of full moment tensors for Hungary using waveform inversion technique

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We have successfully estimated the full moment tensors of 22 local earthquakes with local magnitudes between 1.2 and 4.8 in the Hungarian part of the Pannonian basin using a probabilistic waveform inversion procedure. The estimated uncertainties in the moment tensor components are plotted on the focal sphere in such a way, that the significance of the double couple (DC), the compensated linear vector dipole (CLVD) and the isotropic (ISO) parts of the source can be assessed. The non-DC components of the retrieved focal mechanisms are statistically insignificant for all the analyzed earthquakes. The negligible amount of the ISO component implies the tectonic nature of the investigated events. The moment tensor solutions reported by other agencies for five of the ML>4 earthquakes studied in this paper are very similar to those calculated by the applied waveform inversion algorithm. We have found only strike-slip and thrust faulting events, giving further support to the hypothesis that the Pannonian basin is currently experiencing a compressional regime of deformation. The orientations of the obtained focal mechanisms are in good agreement with the main stress pattern published for the Pannonian region. The azimuth of the sub-horizontal P principal axis varies from about NNE-SSW in SW Hungary through NE-SW well inside the basin to around E-W in the NE part of the country. Most of the analyzed earthquakes occurred on faults or sub-faults differently oriented than the main fault system, indicating that the area is tectonically complex.

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S01p-560

A local seismic network and automatic data processing around a planned nuclear power plant

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A new nuclear power plant is planned at Pyhäjoki, Finland. Pyhäjoki is situated in the central part of the Fennoscandian Shield, a region characterized by low intraplate seismicity. This study presents a seismic monitoring plan around the site. Seismic monitoring is required by IAEA guidelines. The local seismic network collects data for seismic source characterization, seismotectonic interpretations and for monitoring seismic activity. The detection and location capability of the network were simulated by computing spatial azimuthal coverages and detection threshold magnitudes using different station configurations. The network should be dense enough to fulfil the requirements of azimuthal coverage better than 180° and automatic event location capability down to ML~0 within a distance of 25 km from the site. The study identified that a network of 10 stations would satisfy these requirements. The detection thresholds magnitudes are estimated to be M=-0.1 and M=0.1 within a radius of 25 and 50 km from Pyhäjoki, respectively. The expected number of earthquakes detected annually is 3 within 25 km radius and 7 within 50 km radius. The location accuracy within 25 km radius is estimated to be 1-2 km and 4 km for horizontal coordinates and depth, respectively. The network is dense enough to map out faults with horizontal precision of 1–2 km within 25 km radius of the site.

Automatic processing and analysis of the planned seismic network is presented. Following the IAEA guidelines, real-time monitoring of the site area is integrated with the automatic detection and location process of the national seismic network. At the end of year 2014 all together 5 stations have been installed. During preliminary phase about 15 small earthquakes were detected within 20 months.

IASPEI (Seismology, Geophysics)

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S01p-561

Spatial variations of the Vp/Vs ratios and b-values beneath the West Anatolian Extensional Province in Turkey

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Spatial variations of Vp/Vs ratios and b-values beneath the West Anatolian Extensional Province (WAEP) are investigated to understand the physical properties of the crust. The Vp/Vs ratios are estimated from the slope of the Wadati diagram using a new earthquake catalogue which was produced by a dense network (July 2007- February 2011; $M_L \leq 5.1$; 23,335 earthquakes with Mc ~1.4). While low Vp/Vs ratios (1.56-1.74) are estimated for silica rich rocks of the Menderes Massif, high Vp/Vs ratio (1.75-1.91) are correlated with silica poor and deep rocks along the faults bounding the Menderes Massif. Spatial distribution of the b-values estimated from the frequency magnitude distribution generally shows low b-values, except a relatively high b-value zone in the Denizli Basin to the east of the study area. While the depth distribution of the b-values are relatively low in the upper 10 km of the crust along the Profile I, which cuts the region in EW direction from Kusadasi to Denizli, the b-values beneath the Profile II in the Denizli Basin, are locally high (>1.2) in the distance range between 15 and 45 km, presenting a concave shape towards the deeper part of the section. Generally, we have interpreted that spatial variations of Vp/Vs ratios and b-values in this study are related to the fault controlled geothermal systems in the study area.

IASPEI (Seismology, Geophysics)

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S01p-562

Automatic classification of regional seismic events with Support Vector Machine

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An automated method for seismic event classification within a sparse regional seismograph network is presented. The tool is based on a supervised pattern recognition technique, Support Vector Machine (SVM). The SVM is trained to distinguish local and regional earthquakes from man-made or spurious seismic events in fully automatic detection logs. The classification rules utilize spectral information extracted from the total duration of seismic signals. SVM models were calculated for 19 permanent seismic stations in Finland. The number of earthquakes and other events was station-specific and varied between 11-268 and 223-1017, respectively.
In order to find the best voting rules for combining the results from different stations, a test data base comprising 1190 fully automatic seismic event determinations was used. According to the manual analysis 98 % of the events were explosions or noise and 2 % earthquakes. With the best voting rules 91 % of the non-earthquakes and all the earthquakes were correctly identified. The network processing rules were applied to an evaluation period of 188 days. The data comprised 2342 fully automatic event detections. With the SVM method 93 % of the non-earthquakes and all the earthquakes were correctly identified.
The results imply that the SVM tool can identify and filter out blasts and spurious events automatically with a high level of confidence. The tool helps to reduce work-load in manual seismic analysis by leaving only 7 % of the fully automatic event determinations, i.e. the probable earthquakes for a more detailed manual analysis. The capability of SVM is compared with other methods.

IASPEI (Seismology, Geophysics)

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S01p-563

The monitoring of the local seismic activity in Romania – performance level of the present national seismic network

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The seismic source located in the subcrustal lithosphere at the bend of Eastern Carpathians (in Vrancea region), which may generate events with magnitude $M_w >$ 7.0, controls the seismic hazard over wide areas in southern and eastern Romania. Apart from the source of intermediate depth earthquakes, several crustal source zones of local importance are present in western, central and eastern Romania.

The seismic activity throughout the national territory is continuously monitored by the seismic network operated by the National Institute for Earth Physics of Bucharest.

A considerable effort carried out during the past years, mainly since 2008, has resulted in 118 permanent digital stations in operation at present – 99 stations with real time data transmission and 19 off-line stations. All stations are equipped with 3-component accelerometers, while most of the on-line stations are equipped with velocity sensors as well.

The goal of this study is to evaluate the overall performance of the network, in its present configuration, regarding the monitoring of the local seismicity, and to quantify the value of the individual stations for the localization of the seismic events on the territory of Romania. The station effectiveness is estimated by taking into account the fraction of events that are localized using the station data (compared to the total number of events of the national catalogue, which occurred during the time of station operation), and the location of the station site with respect to the seismogenic zones.

The analysis provides a measure of station reliability, and yields essential information for decisions regarding the effectiveness increasing and future development of the network.

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The International Training Center at the premises of KNDC as a result of Kazakhstan-Norway cooperation

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The International Training Center was established at the premises of KNDC in Almaty (Kazakhstan) under financial and methodical support of the Norwegian MFA and NORSAR. The Center task was to re-establish the cooperation of Central Asian seismologists that was lost after the USSR collapse, arrange data exchange and activate joint research work. Since 2010, for the specialists of five Central Asia countries there were 12 one-month courses on interpreting and processing of seismograms in support of the CTBTO, 4 seminars on techniques of analog seismograms digitization and technical maintenance of monitoring stations, and courses on GEOTOOL operation. In total, 58 specialists participated in the training courses. Lectures and practical exercises for the trainees are given by the KNDC staff having large practical experience on working with seismological data, and some lectures are given by specialists invited from abroad. The seismologists from different countries mastered the common data formats for storage and exchange of information, and the techniques on source location and discrimination of events nature. During the courses, the trainees are informed about monitoring networks development, and new methods for data processing. The next aim of cooperation is the creation of an operational seismic bulletin for Central Asia countries.

IASPEI (Seismology, Geophysics)

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Finite source inversions using strong motion waveforms of Taiwan TSMIP data

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Inverting seismic waveforms for the finite fault source parameters of earthquakes is important for reconstruction of faulting processes including both the properties of the fault and transient stress field. It is also significant to image seismogenic structures in urban areas. Here we analyze the finite-source process and test for the causative fault plane using the accelerograms recorded by the Taiwan Strong-Motion Instrumentation Program (TSMIP) stations. The point source parameters for more than 100 Mw>4 earthquakes were first obtained by complete waveform moment tensor inversions. Then we use part of this catalog to study the 22 October 1999 (Mw 5.6) earthquake sequence near the city of Chiayi, Taiwan, where a damaging earthquake occurred a century ago. We have derived a slip distribution model of this mainshock using a finite fault inversion code developed by Dreger and Kaverina (2000). We also have tested different input parameters (hypocenters, rupture velocities, dislocation risetimes, and different combinations of stations) to determine their influence on inversion results. To further characterize the faulting, we analyzing the GPS displacement data for the pre-event, coseismic, and postseismic epochs. Preliminary results show the mainshock ruptured on the NNE-SSW trending right-lateral strike-slip fault and propagated toward SSW direction with an asperity of 8 km by 3 km. The procedure developed from this study can be applied to other earthquakes, e.g. 2 June 2013 Mw 6.2 Nantou earthquake to better understand kinematic source parameters of Mw5 and Mw6 earthquakes.

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S01p-566

Cooperation between the ISC and the arkhangelsk seismic network

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Arkhangelsk seismic network is a full partner of the International Seismological Centre (ISC). An agreement of cooperation was signed by the Institute of Environmental Problems of the North of the Ural Branch of Russian Academy of Science (IEPN UB RAS) and the ISC in 2014.
The main goal of the Arkhangelsk seismic network is the seismic monitoring of the European part of Arctic and the monitoring of strong earthquakes in collaboration with the Geophysical Service of RAS. The result of the monitoring is a) seismic catalog that contains information about epicenters of seismic events and b) seismic maps, which can be found at http://www.iepn.ru/?page=186.
Seismic bulletins of earthquakes in European part of Arctic are conveyed to the ISC starting from December 2012. ISC catalog is actively used in Arkhangelsk seismic network for routine analysis and the evaluation of seismic activity including the following tasks:
- Determination of the velocity structure of the lithosphere of the northern part of Russian Plate;
- Analysis of the historical seismicity of the Barents region;
- Efficiency assessment of regional hodographs.
A group of insular seismic stations is planned for construction in the framework of the Arkhangelsk seismic network. These stations are expected to provide data essential for the ISC.

IASPEI (Seismology, Geophysics)

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S01p-567

Potential indicator of moment tensors with isotropic component – results for synthetic tests and two contrasting Greek shallow earthquakes

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Non-double-couple (non-DC) components of moment tensors (MT) play a key role in our understanding faulting processes of earthquakes and/or identifying explosions. Opposed to double-couple (DC) components of the calculated seismic source model, the non-DC components (CLVD and the isotropic part ISO) are strongly sensitive to error in location, inaccurate velocity model, and noise. Therefore, methods for analyzing resolvability of ISO had to be developed (e.g. Krizova et al., 2013). It is particularly important to identify events whose ISO component is trustable. This contribution aims to highlight a possible indicator. Recent MT determinations include space and time grid search (e.g. Sokos and Zahradnik, 2008, 2013). The centroid is identified in one of the trial source positions by maximizing correlation between real and synthetic waveforms. In synthetic tests with varying ISO percentage we compare the correlation-depth dependence for the full and deviatoric MT. We show that in calculations for deviatoric MT, the events with significant isotropic components are characterized by local minima of the correlation, occurring near the true source depth. In this way, the assumption of the deviatoric MT may strongly bias the centroid depth estimate. On the other hand, when we compare the grid-search results under the deviatoric and full MT assumptions, their difference may serve as an indicator of the significant ISO. This straightforward method is applied to two shallow earthquakes in Greece (Cretan Sea, 27th January 2012, Mw 5.3 and Santorini earthquake, 26th June 2009, Mw 4.9). It indicates a very small and large ISO in the first and second case, respectively.

IASPEI (Seismology, Geophysics)

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S01p-568

Characteristics of 2013 Yellow Sea events, Korea

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Seismicity in and around Korean Peninsula is low compared to surrounding regions, such as Japan, China and Taiwan. The largest instrumentally observed earthquakes are less than local magnitude (ML) 5.5. About forty earthquakes (ML≥2) have been reported by the Korea Meteorological Administration (KMA) in a year since the digital seismic network was constructed. KMA, however, reported 93 earthquakes in 2013 and 72 events occurred in the Sea, especially 52 quakes in the Yellow Sea. Most of them are three main events and fore- and after-shocks. The first (Shinan) event occurred on 21 April, with ML 4.9. The second (Baengnyeongdo) and third (Boryeong) events occurred on 18 May and 13 July and the local magnitudes were 4.9 and 3.5, respectively. To understand the characteristics of seismicity in Korea, we investigated fore- and after-shocks of three events, relocated and determined focal mechanism or moment tensor solutions of main events. As a result, Boryeong earthquakes with M<1, M1~2, M2~3 and M>3 identified 144, 142, 27 and 2 events, respectively. 182 out of 315 quakes were relocated and distributed in NE-SW direction, within a range of about 1 km width and 4 km lengthen and focal depths range from 14 to 18 km. In the case of Baengnyeongdo event, 388 fore- and after-shocks were confirmed and earthquakes with M<1, M1~2, M2~3, M3~4 were 288, 85, 12, 3 events, respectively. The focal mechanism and moment tensor solutions of these two main events also represented strike-slip faulting including minor thrust component and main stress direction showed NE-SW direction. We will show the results of the Shinan event in presentation, and compare the seismicity patterns of the three events.

IASPEI (Seismology, Geophysics)

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S01p-569

Adjoint tomography imaging of the crustal structure beneath the Kanto Plain in Japan

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We have obtained the preliminary model of three dimensional (3D) structure beneath the Kanto Plain, metropolitan area of Japan. We applied the spectral-element method (e.g. Peter et al. 2011) and adjoint method (Liu and Tromp 2006) to infer 3D velocity model and to reproduce the observed waveform bandpass filtered between 5 and 20 second. We used the travel-time tomography result (Matsubara and Obara 2011) as an initial 3D model and used broadband records obtained at the NIED F-net stations. We selected 147 earthquakes based on the earthquake catalog by the F-net and the S/N ratio of their seismograms. The 3D model used for the forward and adjoint simulations is represented as a region of approximately 500 by 450 km in horizontal and 120 km in depth. Minimum period was 4.35 second. The initial 3D model reproduced P-wave seismograms well, however it could not really explain S-waves and later arrivals. For the adjoint inversion, we picked up the windows of the body waves from the observed and theoretical seismograms. The forward and adjoint simulations were implemented by K-computer in RIKEN. One iteration requires about 0.1 million CPU hours at least. The model parameters of Vp and Vs were updated by using the steepest descent method. The revised model reproduces observed waveforms better than the initial model. Acknowledgements: This research was partly supported by MEXT Strategic Program for Innovative Research. We thank to Dr. Daniel Peter for his comments and suggestions. We also thank to the NIED for providing seismological data.

IASPEI (Seismology, Geophysics)

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S01p-570

A four-stage model of earthquake dynamics by means of precursory high frequency fracture induced electromagnetic emissions

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Since 1994, a telemetric remote station has been installed in a carefully selected mountainous site using the same instrumentation as in laboratory experiments for the recording of fracture-induced pre-fracture kHz and MHz magnetic and electric fields, respectively. Linking these electromagnetic (EM) observations to corresponding distinctive last stages of the fracture / earthquake preparation is of crucial importance in understanding them. Based on a multidisciplinary analysis, the following four-stage model of earthquake dynamics by means of precursory EM emissions has been proposed. The initially observed MHz EM anomaly is due to the fracture of the highly heterogeneous system that surrounds the formation of strong brittle and high-strength entities (asperities) distributed along the rough surfaces of the main fault sustaining the system. The MHz EM emission can be described by means of a second-order phase transition in equilibrium. The abruptly emerging strong sequence of kHz EM avalanches originates in the stage of stick-slip-like plastic flow, namely, the fracture of asperities themselves. The burst-like kHz EM emission does not present any footprint of a second-order transition in equilibrium. Between the aforementioned two stages of fracture process, an intermediate stage exists which shows tricritical behavior. Finally, the systematically observed EM silence in all frequency bands before the time of the earthquake occurrence is sourced in the stage of preparation of dynamical slip which results to the fast, even super-shear, mode that surpasses the shear wave speed.

IASPEI (Seismology, Geophysics)

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S01p-571

North America and China regionalization based on clustering analysis of receiver functions.

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Current state-of-the-art of receiver functions is to image lateral variations of major seismic boundaries thanks to the ongoing staggering instrumental effort. Here, we test the coherence of receiver functions with known tectonic and physiographic features and/or geophysical information related to the crust through model regionalization.

We present a similar clustering analysis than the approach of Lekic & Romanowicz (2011) in which regionalization is performed through a cluster analysis of tomographic velocity models but based on P-wave receiver functions instead. We explore other metrics than L2 as measure of distance and resampling of the time-series due to the high degree of clustering of receiver functions. Quality of clustering is assessed through both, the percentage of variance explained within the clusters, and the ratio of the minimum distances between clusters and data. Coherence and association of obtained clusters with known regionalization characteristics will be also presented.

We first validate our clustering technique in Western US for which several datasets were available to us. A first set of 483 time series was built by stacking EARS receiver functions for each available station across all azimuths and with a Gaussian filter width of 2.5 Hz and small ray parameters (0.038 to 0.05 s/km). The second dataset was built by interpolation of the receiver function wavefield (Chai et

al., GRL, in review) with bins on 2 Gaussian widths and 3 ray-parameters. The agreement with tectonic regions is better for the second dataset.

Our collaborators in China provide us with the second dataset consisting of teleseismic P-wave receiver functions for 785 stations. Preliminary clustering results are encouraging, and we will show our first attempts to regionalization.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-572

Using neural networks to study the long series of seismological data to identify precursors of strong seismic events

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To minimize the risk and the destructive effects of strong seismic events it is essential to initiate an appropriate warning ahead of time. We are developing a method to facilitate the process of forecast of strong earthquakes based on observations of the travel time of the longitudinal and transverse P- S- waves and their ratio from local earthquakes recorded by a regional network of seismic stations in the region under study. In order to improve the reliability of earthquake prediction one must take into account a variety of factors related to the process of preparation of earthquakes. We study the reflection of the process of preparation of earthquakes in the field fluctuations travel times of P and S wave velocity ratio of these waves change them in time and space. Based on the data recorded by seismic stations detected kinematic harbinger of strong earthquakes. Analysis of prognostic parameters was performed on a long series of data on the parameters of hypocenters and travel times from earthquakes focal zone of Kamchatka and the active regions of the Caucasus. Identifying precursors used for analysis using Neural Network Pattern Recognition, a neural network with one input layer, one hidden layer and one output layer. Discloses a general scheme based on this prediction of the neural network with a particular selection rule vector purposes.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-573

Application of modified short-period seismometer for earthquake monitoring

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Seismic monitoring is a recognized tool for monitoring changes in the stress-strain state of the environment, the geodynamic situation and identifying dangerous trends at an early stage. Depending on the set of physical problems transducers of different types corresponding to the desired frequency range are used. Application of modifying sensors with enhanced amplitude-frequency features provides the same results as the standard equipment at a reasonable cost. The paper analyzes the seismic events for testing methods of numerical correction in terms of the short-period sensor CM-3KV (natural frequency of 0.5Hz). Determination of seismic events magnitude is performed by standard methods for the maximum amplitude of the P- and surfaces waves velocity. Evaluation of the application limits of measuring channels for seismometers and microseismic noise registration show the ability of the modified sensors to detect surface waves from strong distant earthquakes that were previously beyond their capabilities. Extension of the frequency response of the sensor CM-3KV is performed for earthquakes 7.0 <Mw <7.5 (Catalog Global CMT Catalog) at teleseismic distances. For these events maximum amplitude velocities for P- and surface waves recorded by modified CM-3KV and broadband sensor are estimated. The calculated values of velocity are used to estimate an error in determining the different types of magnitude (for body waves and surface wave) for the modified sensor. Error in determining the magnitude of short-period seismometers with extended frequency response used for earthquake monitoring corresponds to the accuracy of estimates of magnitudes in seismic catalogs.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-574

Seismicity of the Lofoten area, Norway

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The Nordland area (65-70N; 8-18E) was proved as the tectonically most active part of Norway. Enhanced seismicity together with uplift in this area deviate from the long-wavelength pattern, usually attributed to glacial isostatic adjustment (related to Pleistocene unloading). Detailed monitoring of seismic activity in the Nordland area started in 2013 as a part of the NEONOR2 project and information obtained from analysis of earthquakes together with geodetic data should be the key inputs for modeling of deformation and uplift patterns and their mechanisms in the region.

Local/regional network of 26 broad-band stations were deployed which together with the permanent NNSN stations consist 32 stations within span 350 x 200 km. About 220 earthquakes of M>1.0 were recorded between Sep 2013 and Feb 2015. The main aim of the project is to reveal the stress field in that particular region. Therefore the detailed analysis of individual events was performed including precise relative locations, space-time migration analysis, search for fault plane solutions and moment tensor (MT) inversion. As the first onset of the P-wave arrival is often emergent at most of the stations, the inversion of the MT is also performed by using the spectral amplitudes. The methods for the MT inversion are compared and analysed on selected earthquakes.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-575

Seismic activity in the southern source region of the 2011 Tohoku earthquake by long-term ocean bottom seismometers

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The 2011 Tohoku earthquake occurred along the plate boundary and many aftershocks followed. Just after the mainshock, urgent seafloor seismic observations were performed and the precise aftershock distribution in the source region was obtained. To continue monitoring of a precise seismic activity is important for consideration of large earthquake generation. In order to monitor the seismic activity after the mainshock, we carried out seafloor seismic observations using long-term ocean bottom seismometers (LT-OBSs). We deployed 40 LT-OBSs in the whole source region in September 2011 and have completed recovery of the LT-OBSs until November, 2012. Additionally 40 LT-OBSs were deployed in the southernmost source region of the mainshock in April, 2012. In the autumn of 2012, 40 LT-OBSs were recovered and other 40 LT-OBSs were installed in adjacent area. The observation continued to October, 2013. We selected events whose epicenter is located below the network form the land-based earthquake catalog, and P and S-wave arrival times were picked. Hypocenters were estimated by a maximum-likelihood estimation technique with one dimensional velocity structures. Thickness of sedimentary layer changes was evaluated and the estimated travel times by the location program were adjusted. Most of the hypocenters have

depths shallower than 40 km. The events form a plane dipping landward. We compare locations of the hypocenters with those of the aftershock just after the mainshock. In the aftershock distribution, the low-seismicity region is recognized at the plate boundary in the off-Fukushima region. On the other hand, our results show the seismicity is not low in the identical region. A stress change at a ruptured plate boundary is inferred.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-576

Estimation of subsurface structure using microtremor in Karaj city, Iran

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In order to estimate the site effects in Karaj city, microtremor H/V spectral ratios were used in 37 places of the city. The result represents that the dominant frequency ranging from 0.4 to 2 Hz. The results of H/V spectral ratio affected by local geologic structure, based on this assumption, we can produce theoretical H/V curve with knowledge of the geologic structure in the area. Therefore, one-dimensional modeling was carried out with Deepsoil software using the linear method at low strain in three steps. First, downhole data studied that were available maximum depth of 50 meters. So low thickness of alluvium about 17-30 meters were considered with engineering bedrock (>760 m/s) which represents higher frequency range compared with the microtremor data. According to reliability of experimental H/V results that has been demonstrated by researchers around the world, the difference between the results of transfer function in experimental and theoretical methods indicates that the model has not been properly for two variables of shear wave velocity or depth of bedrock and alluvium thickness. So modeling was carried out considering the greater depth of alluvium on geology bedrock (1300 m/s) using shear wave velocity profile obtained from microtremor array data. The results of this modeling have a good agreement with H/V microtremor peaks, indicated an effective contrast at a depth of 200 to 300 meters; however, transfer functions obtained in this model not covered low frequency peaks in the experimental methods. To obtain a better model, deep contrasts were considered about 2 kilometers according to the geological conditions of the region due to differences kind of materials in bedrock, so the result of this modeling has a good agreement with H/V microtremor peaks.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-577

Performance test of first body-wave arrival times for constraining a slow mantle wedge in a subduction zone

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The present study demonstrates how much the values of velocity in a low velocity region at a mantle wedge can be constrained by using first arrival times of body waves in 3-D traveltime tomography, based on numerical experiments. In a subduction zone, water can be dehydrated from a subducting oceanic plate. The dehydration reactions depend on pressure and temperature in the subducting plate, and released water is moved into the overriding crust or mantle, sometimes causing hydration reactions. The water and the metamorphic reactions can change seismic wave speeds in the region. To understand the nature associated with water and the reactions in and around the subducting plate, values of seismic velocity are often useful. The distribution of seismic velocity in a subduction zone is imaged by the techniques of seismic tomography. In many studies, times of first arrivals of P and S waves are used for data. From the tomographic images, mantle wedges characterized by high values of Vp/Vs as well as low values of Vs have been suggested, possibly as a result of serpentinization. However, when there is a low velocity region, first arrivals of body waves do not always involve direct waves traversing the slow region. In this study, we examine how tomographic images and velocity values can be changed by using first arrival times for seismic tomography, particularly, in a subduction region where the mantle wedge is slow. We will show the results depending on used data and conditions.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-578

Systematic monitoring of seismic instrumentation condition in high-density broadband seismic networks

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Broadband seismometer data are possible to be contaminated by instrumentation response errors that are often difficult to recognize from visual waveform checks. Herein, we report on the development of a systematic method of assessing the seismometer's conditions for recording ground motions at a period range of 50-200 sec in observation networks whose station intervals are as small as 200 km. The method is based on comparisons between teleseismic surface wave records at a target station and those at multiple surrounding reference stations, from which we calculate three index parameters and evaluate in-situ instrumentation conditions, including amplitude and phase responses against ground motions. We applied the proposed method to F-net broadband seismometers covering the Japanese Islands, where station intervals are approximately 100 km. This allows us to evaluate instrumentation health at each station at least once each 60 days. We found that approximately 75 % of the evaluated index parameters distributed well around the standard values, and most examined broadband seismometers worked properly. However, instrumentation errors, such as gain decrease and gradual changes in amplitude and phase responses, were identified at a few stations. Additionally, over-damping errors at the STS-1 seismometers, which experience significant amplitude and phase response variations around the 360-sec corner, appear to have been common at several stations. In contrast, STS-2 seismometers appear to have functioned more reliably than STS-1 seismometers. It is believed that the systematic evaluation of instrumentation health will enhance the operation of seismic networks.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-579

Revision of the NE Iberian peninsula instrumental catalog in terms of location quality parameters

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NE of the Iberian Peninsula is nowadays a moderate seismic area, but in historical periods there have occurred major earthquakes. The seismic activity occurs mostly in the axial zone of the Pyrenees and in the Mediterranean area, both on the coastal range and the continental shelf.

The Institut Cartogràfic i Geològic de Catalunya (ICGC) manages a seismic network, which started during the 1980 decade with short period analogic stations. Since 1999 stations based on VSAT platforms were installed. They are continuously transmitting data in real time via satellite to the ICGC hub. At present, this network consists of 20 seismometers, 17 broad-band and 3 accelerometer sensors.

Since 1984 a seismic catalog based both on own and collaborating agencies' data is elaborated. In this work we analyze the local seismic activity in relation to the uncertainties of the hypocentral locations. The methodology consists in obtaining a homogeneous seismic catalog, relocating all earthquakes through a single program, Hypocenter. We analyze the parameters that characterize the hypocentral location quality and define four quality classes, A, B, C and D, where A is the best and D is the worst.

The homogeneous catalog is composed of 9692 events with a maximum magnitude of 5.2. The analysis shows that the evolution of the network involves an improvement of the hypocentral locations quality. Before 1999 there are 2265 events and the completeness of the catalog is magnitude 2. During this period, A quality locations represent a 1% of the catalog and D quality locations, a 40%. After 1999, with 7427 events and a completeness of magnitude 1, there is a 3% of A and a 28% of D quality locations.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-580

Aftershock sequence analysis of the 11 August 2012 doublet earthquakes (Mw 6.5, 6.4) in NW Iran

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The Ahar-Varzghan double earthquakes with magnitudes Mw 6.5 and 6.4 occurred in the 2012 August 11 in NW Iran and were followed by many aftershock. We analyse ~5 month aftershock sequence of these events. The Ahar-Varzghan earthquakes occurred along complex faults and provide a new constraint on the earthquake hazard evaluation in NW Iran. The general pattern of relocated aftershocks distribution defines a complex seismic zone covering an area of approximately 30×15 km^2. Ahar-Varzghan aftershock sequence shows an abnormal pattern as a secondary aftershock sequence, which started on November 7 approximately 3 month after the mainshock, with a significant increase in activity, regarding both events and their magnitude. This stage was characterized by a seismic area which widened to the west of mainshock. We believe that this is evidence of activity extending west to west-northwest. Relocated aftershocks locations show a broad zone clustering west to west-northwest that dips toward the south at about vertically which is interpreted as the fault plane of the mainshock (first shock M_W 6.5). Temporal and special distribution of relocated aftershocks shows that those related to a significant tectonic feature instead of random occurrence. We found that the aftershocks migrated in both along-strike and up-dip directions.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-581

Rupture model for the 2011 Tohoku-Oki earthquake from high-rate and ocean-bottom GPS

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High-rate GPS data provides abundant information of an earthquake rupture. So far some studies of finite source rupture processes for earthquakes using high-rate GPS data are reported. However the previous rupture models for different events are all based upon a priori rupture velocity. In this paper, using the “zero rupture delay time” approach, we inverted a rupture model with varying rupture front expansion velocity for the 11 March 2011 Tohoku-Oki megathrust from the high-rate GPS records in Japan islands and ocean bottom GPS/acoustic data. The inverted rupture velocity of complex distribution has gradually increasing near the hypocenter and shows a rapid rupture expansion near the trench. The overall rupture process includes three energy release time periods, covering the whole duration of 160 s. The preferred slip model, showing a compatible relationship with aftershocks and afterslip distribution, has a primary asperity concentrated from the hypocenter to the trench and a small asperity located on the southern fault. Results of source time functions for subfaults and temporal rupture snapshots suggest repeated slips occurring in the primary rupture region; and slip at the shallow fault triggered rupture of the deeper beneath the hypocenter which is consistent with that from seismic waveforms. Our maximum slip and total seismic moment are ~65 m and 4.3×10^{22} Nm (Mw 9.0), respectively.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-582

Automated determination of local, regional, and teleseismic P- and S-phase onset time at German Regional Seismic Network

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With the availability of large amounts of waveform data from broadband seimic networks the automation of P- and S-onset time determination becomes more and more important. A number of automated routines have been developed for the picking of P and S phases for relocation of the regional and local events, for regional tomography and monitoring of seismicity, based on the STA/LTA as well as on autoregressive (AR) prediction. Here, an automatic picking tool based on multi-component autoregressive prediction and the Akaike Information Criterion (AIC) is applied to P- and S-phases at local to teleseismic distances. The main points addressed by an automatic picking tool is the robustness of the implemented algorithm in terms of reproducibility and consistency of the picks and its precision as well as the phase identification, and quality estimation of the picks. The proposed picker is based on a Characteristic Function and a Cost Function. The Characteristic function describes the properties of the signal and of the phase to be picked. The phase onset is then represented by a sharp increase of the Characteristic Function. The Cost Function instead identifies the absolute minimum of the Characteristic Function before its sharp increase and uses as penalty the distance from the AIC minimum (identified with the latest possible pick) and smooth changes of the Characteristic Function. The picker is tested to different parametrizations to evaluate the reproducibility of the picks and the sensitivity to the various input parameters. The set of parameters is then optimized for each phase of interest and frequency content of the signal. Here we present automated picks for local, regional and teleseismic P- and S- phases at the stations of the German Regional Seismic Network.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-583

Seismic noise in Turkey

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The Earthquake Department of Prime Ministry Disaster and Emergency Management Presidency (AFAD) operates a seismic network of more than 200 broadband stations distributed over Turkey. We computed noise power spectra for this network to produce probability density function plots and spectrograms using the SEISAN software package. The observed noise levels result from a number of factors including the natural ambient noise, the vault construction and the instrumentation. The objectives of this work were to 1) map ambient noise levels across Turkey for different frequency bands; 2) develop noise models for Turkey; 3) evaluate the vault construction; 4) identify instrumental problems. A number of technical issues were identified related to the vault construction or instrumentation and recommendations on solving these were made. The low and high noise models developed are the first specific models developed for Turkey and will help with the planning of new stations. Across the network, we found that the microseismic peak noise levels related to ocean waves are close to the global low noise model. However, for coastal stations we found that noise levels increase around periods of about 1 sec. The mapping of noise levels at higher frequencies helped to account in the computation of detection maps for particularly noisy stations. The computation of noise levels was also established at AFAD as a routine quality control monitoring tool.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-584

Variable multi-window method of source time function in rupture process inversion

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Variable multi-window method (VMWM) of source time function is an extension of traditional linear multi-window method (MWM), that strengthens the detail control of source time function in subfault. VMWM first limit the allowable rupture time of each subfault into a certain range by maximum rupture velocity and minimum stop velocity, then discrete the determined rupture time using isosceles triangles. Different from MWM, VMWM allows subfaults to have different rupture time and rise time, and use variable multi windows to parameterization the source time function then construct the spatial-temporal rupture process. Iteration inversion is used to gradually narrow the allowable range of rupture time of each subfault till a small enough one is achieved. Then detailed slip distribution, rupture time and rise time are inverted.

The superiorities of VMWM over traditional MWM are as following:

Different degrees of discretization are allowed in different areas on fault plane. VMWM would like to intense the initial rupture area and sparse the area of near fault boundary.

There is no need to search average rupture velocity in VMWM. VMWM reduce the rupture range time from iteration inversions, which does not need to search an average rupture velocity first.

The consistence of complex rupture process for source time function parameterization from traditional MWM and single-window searching method to Wenchuan earthquake, China, which has super-long rupture time and complex variation in rupture velocity, would be much difficult. Rupture process of Wenchuan earthquake using VMWM is satisfactory and deep analysis of the result is conducted.

IASPEI (Seismology, Geophysics)

S01p - S01/S01f Seismological Observation and Interpretation: Open session, Seismic Time series Analysis

S01p-585

Developing regional multiband magnitude scale for Kamchatka earthquakes: stage 1

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A multiband magnitude (MBM) is understood as a set of magnitude-like parameters determined for a set of frequency bands that jointly cover a broad frequency range. Two classes of MBM are planned. The first one is multiband amplitude-based magnitude (MBAM). It uses distance-normalized peak amplitudes of filtered P and S (or maybe S+Love+Rayleigh) wave groups. It follows the line of CHISS or spectral magnitude of Zapolski, Rautian and Duda. The second one is multiband energy magnitude (MBEM). It uses distance-normalized levels of amplitude spectrum of P and S wave groups within a band. Especially accurate estimates of spectrum can be based on the time-normalized level of filtered coda. Unfortunately, coda measurements are often impossible because of low S/N ratio. Therefore coda-based MBEM can be supplied only for a limited part of earthquake catalogue. The eventual use of MBM by Kamchatka seismic network will significantly broaden the standard description of source properties of an earthquake listed in the regional earthquake catalogue, and permit detailed analysis of average as well as peculiar spectral properties of tectonic and volcano-tectonic events. Eventually, MBEM scale may be augmented by absolute calibration, permitting one to estimate in routine mode moment rate spectrum of each recorded event.

The first stage of development of regional MBM technique are presented. Newly estimated calibration curves (standard functions of amplitude decay with distance) for MBAM will be shown for Kamchatka earthquakes. These curves for P and S waves are specified for 2/3-octave filters that jointly cover the 0.04-2 Hz range. Also, coda decay curves aimed for MBEM determination, average for Kamchatka region, will be presented, covering the same range.

IASPEI (Seismology, Geophysics)

S01aa - S01a Seismological Observation and Interpretation: Seismic Swarms and Tectonic Tremors

IUGG-1101

Modeling of earthquake swarm in terms of slip-induced dilatancy coupled with fluid flow

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Hainzl and Ogata (2005) and Yukutake et al.(2011) demonstrated that stress triggering dominates the earthquake swarm activity at its later stage of evolution whereas the fluid flow contributes to the initial process of the swarm activity. If this is the case, questions arise as to why triggered ruptures remain to be small-size events and why such small-size ruptures occur repeatedly at the later stage of swarm activity. Slip-induced dilatancy will be a mechanism to stabilize the slip evolution, which tends to suppress the event size (Yamashita, 1999). However, slip-induced dilatancy alone cannot model long duration earthquake swarm. We propose here that slip-induced dilatancy coupled with fluid flow is involved in the generation of swarm-like activity especially at its later stage. In this modeling, we do not have to assume locally elevated fluid pressure to drive the slip evolution. In our model, once a rupture is nucleated for some reasons, fluid begins to flow into dilatant slip zone from fluid-saturated surrounding medium, which gradually elevate the fluid pressure in the slip zone and slowly advance the rupture tip. However, healing rate of slip surface should be small enough for the occurrence of rupture that continues for prolonged periods. The nucleated rupture will not grow into unstable one if the slip-induced dilatancy is large enough and the medium is saturated with high-pressure fluid. Our calculation shows that the growth rate of rupture is smaller for higher degree of slip-induced dilatancy. If the spatial distribution of model parameters is smooth enough, the slip evolution is found to be creep-like, which may be consistent with the observation of Bourouis and Bernard (2011), who found aseismic fault slip during water injection.

IASPEI (Seismology, Geophysics)

S01aa - S01a Seismological Observation and Interpretation: Seismic Swarms and Tectonic Tremors

IUGG-1992

Detection of shallow crustal discontinuities from high-frequency waveforms of swarm earthquakes in West Bohemia/Vogtland seismoactive area

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In our study we concentrate on retrieving a shallow velocity structure in the upper crust. The upper crustal structure is studied from waveforms of local micro-earthquakes that occurred during the 2008 swarm in West Bohemia/Vogtland seismoactive region. They were recorded by the WEBNET network consisting of 22 three-component seismic stations. We focus on high-frequency PS and SP converted waves generated at shallow interfaces at depths between 2 and 5 km. Apart from the velocity contrast at the interfaces, the amplitudes of converted waves are significantly affected by the source-receiver geometry and by the focal mechanisms of the earthquakes. This observation complicates the analysis, being absent in processing of standard active seismic experiments with sources of rather uniform radiation. The strong dependence of amplitudes of reflections/conversions on focal mechanisms and on the source-receiver geometry is confirmed by synthetic tests, which reveal preferential azimuths suitable for interpretation of data. We apply reflection seismic approach with data rotation into multi-azimuthal sections, data alignment and stacking to amplify reflected/converted phases, the ray tracing for calculation of the exact arrival times of phases, analysis of reflection/transmission coefficients in order to assess the amplitudes in real waveforms, synthetic modelling of full waveforms using the discrete wave number method to compare synthetic full wave fields with recorded data, and the grid search algorithm as the robust inversion method. Good azimuthal coverage of stations and proper attention paid to focal mechanisms and to the source-receiver geometry, and especially their impact on the final shape of waveforms will enable to retrieve the topography of interfaces.

IASPEI (Seismology, Geophysics)

S01aa - S01a Seismological Observation and Interpretation: Seismic Swarms and Tectonic Tremors

IUGG-2021

The Pollino Seismic Sequence: Activated Graben Structures in a Seismic Gap

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The Mercure Basin (MB) and the Castrovillari Fault (CF) in the Pollino range (Southern Apennines, Italy) represent prominent seismic gaps in Italy, lacking M>5.5 earthquakes during the last centuries. The region has been interested by swarm seismicity since 2010 culminating in autumn 2012 with a M=5 event. Forming a graben-like structure the range hosts opposing normal faults with unknown rheology and interaction. The seismic potential of MB and CF and the deformation style have been debated. Based on the recent seismicity we study the behaviour of the faults.
GFZ and INGV have been monitoring the seismicity by a small-aperture seismic array within a network. More than 60,000 local earthquakes between 11/2012 and 09/2014 were detected, >16,000 were located and investigated along with the seismicity since 01/2010. The locations constrain the activated structures and the event migration. The quakes form clusters within the southern part of the MB and along the Pollino Fault linking MB and CF. Most earthquakes are confined to the upper 10 km of the crust in an area of 15x15 km^2. However, sparse seismicity at depths below 15 km and seismicity deepening further north also exists. The CF remains aseismic; only the northern part has experienced micro-seismicity. In agreement with mapped faults, the seismicity interested both eastwards and westwards dipping normal, partially listric faults. They define the geometry of seismically active graben-like structures and were first activated at its centre. At least one cluster shows additional spatio-temporal migration with spreading hypocentres similar to other swarm areas with fluid-triggering mechanisms. The spatio-temporal evolution of this cluster is consistent with pore-pressure diffusion above a normal fault in the graben centre.

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IUGG-2340

"Magma-hydrothermal system and its relation to earthquake swarms at Hakone volcano, central Japan, revealed by dense seismic observation"

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Based on a highly resolved hypocenter distribution and seismic tomography results, we have developed a model associated with the magma-hydrothermal system and the occurrence of earthquake swarms in Hakone volcano, central Japan, where shallow intense swarm activity and crustal deformation associated with inflation of an open crack source are often observed. Using data from the dense seismic network, we found that the earthquake swarms are concentrated in thin vertical plane-like zones, each of which has a thickness of several tens meters. The swarm earthquakes also exhibited a migration of hypocenters that appears to be represented by the diffusion equation: the hydraulic diffusivity is estimated to be approximately 0.5 to 1.0 m^2/s. The observations imply that the swarm earthquakes were triggered by the diffusion of highly pressured crustal fluids within the fault damage zones. By applying travel time data of local earthquakes to a tomographic inversion, we obtained highly resolved seismic velocity structures that show a region of low P-wave velocity (Vp), low S-wave velocity (Vs), and high Vp/Vs ratios at depths of 10–20 km beneath the volcano, corresponding to the location of the open crack source. We suggest that the high Vp/Vs ratios represent a deep magma chamber with a high content of fluid and melt. Above the high-Vp/Vs zone, a region of low Vp, low Vs, and low Vp/Vs ratios exists at depths of 3–10 km, suggesting the presence of crack-filled water or CO_2 supplied from a deep magma chamber. Most of the earthquake swarms occur in this low-Vp/Vs zone. The results indicate that the crustal fluids from the deep magma source substantially contribute to the generation of the earthquake swarms.

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Seismic swarms associated with slow-slip events along the North-Andean subduction zone

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Recent geodetic observations of the subduction zone from Northern Peru to Northern Ecuador reveal that shallow slow slip events (SSEs) frequently occur along this margin. They both affect locked segments of the subduction, like the area of the 1942 Ecuador earthquake (magnitude 8), and the weakly coupled area extending from Northern Peru to Central Ecuador (Nocquet et al., 2014). From 2008 to now, five SSEs, lasting from one week to several months and with equivalent moment magnitudes between 6 and 7, have been geodetically documented. Interestingly, all these SSEs had a clear seismic signature in terms of seismic swarms and did not trigger a clear tremor activity, as observed in numerous other subduction zones. Besides a clear swarm character (shown by the global absence of main shock-aftershock behavior), this associated seismicity tends to cluster in families of similar events. The summed size of all earthquakes during a seismic sequence is always smaller than the SSE in terms of seismic moment, but with a ratio than can vary from a few tenths of percent to a few tens of percent. The two alternative physical interpretations, of seismic swarms being the cause or the consequence of the SSEs, will be discussed in light of three seismic-aseismic sequences, occurring in Central Ecuador (2010), Northern Ecuador (2013), and Northern Peru (2009).

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IUGG-4056

Earthquake swarms induced by magmatic activity: Recent examples from Iceland

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Several magmatic processes produce earthquake sequences that can be classified as earthquakes swarms, i.e. sequences without a mainshock. Recent magmatic activity in Iceland has provided several examples, including the following: Slow inflation of a magma chamber (several cm/year) induces seismic activity in the chamber roof that in some cases can be used to identify a restless volcano. Cases include the eruptions of Grímsvötn in 1983, 1998, 2004, 2011, and the slow inflation of Hrómundartindur in 1994-1998. The inflation may be rapid (a few mm/day) as in the case of the inflation preceding the eruptions and injection events of Krafla in 1975-1977. A few cases are known of slow intrusion of a sill or inclined sheet, like those preceding the eruptions of Eyjafjallajökull in 2010. They occurred in 1994, 1999, 2009, and 2010, each one lasting a few months and accompanied by swarms of small earthquakes. An injection of an inclined sheet in the lower crust at Upptyppingar in the Northern Volcanic Zone lasted a little over a year in 2007-2008 as shown by the accompanying earthquakes and upplift. Persistent „deep“ swarms of low-frequency events have also been detected in four areas in the Upptyppingar - Askja region indicating magmatic movements well below the brittle part of the crust. Injections of dykes have been documented, manifested by propagating earthquake sequences, as in Krafla 1975-1984 (20 cases) and Bárðarbunga 2014. Occasionally rapid deflation of a magma chamber may produce earthquakes, as during the largest two deflation event at Krafla, in 1975 and 1978, and the presently ongoing slow collapse of Bárðarbunga 2014-2015. Most eruptions in the last four decades have been preceded by aprecursory swarm, 20 min. to several hours before the outbreak.

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IUGG-1064

Deformation mechanism and rheology for slow earthquakes

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We detected and located tectonic tremors in subduction zones such as Western Japan, Cascadia, Mexico, Chile, New Zealand, and Taiwan, and along the San Andreas Fault. Behind short-period (> 1Hz) seismic signals recognized as tremors, we can detect very low frequency (VLF) seismic waves in 0.02-0.05 Hz, if noise level is low or after sufficient stacking of broadband seismograms. Signals in the VLF band are useful to constrain the focal mechanism of deformation associated with tremors. Generally the focal mechanism is consistent with shear slip on the plate interface, suggesting the detailed location and shape of the plate interface. The universality of VLF signals behind tremors confirms the hypothesis that these phenomena are only visible parts of broadband shear deformation, which we may call slow earthquakes. The deformation in different places share similar value of moment rates and the total seismic moment is controlled mainly by duration of phenomena. Since most of tremors are sensitive to small tidal stress, the deformation occurs at very low stress level. The tidal sensitivity of tremor is also useful to constrain friction law, or rheology, on the plate interface. Although tremors were discovered on spotty regions of the interface, we expect that similar friction law is acting on much wider region, and controls ordinary earthquakes in seismogenic regions to some extent.

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IUGG-2492

Earthquake statistics, spatiotemporal distribution of foci and source mechanisms - a key to understanding of the West Bohemia/Vogtland earthquake swarms

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West Bohemia-Vogtland is one of the most active intraplate earthquake-swarm areas in Europe which also exhibits high activity of crustal fluids. The Nový Kostel focal zone (NK) dominates the recent seismicity, there were swarms in 1997, 2000, 2008 and 20011, and a striking non-swarm activity (mainshock-aftershock sequences) up to magnitude $M_L = 4.5$ in May to August 2014. The swarms and the 2014 mainshock-aftershock sequences are located close to each other at depths between 6 and 13 km. The frequency-magnitude distributions of all the swarms show bimodal-like character: the most events obey the b-value =1.0 distribution, but a group of the largest events depart significantly from it. All the $M_L > 2.8$ swarm events are located in a few dense clusters which implies step by step rupturing of one or a few asperities during the individual swarms. The source mechanism patters (moment-tensor description, MT) of the individual swarms indicate several families of the mechanisms, which fit well geometry of respective fault segments. MTs of the most events signify pure shears except for the 1997-swarm events the MTs of which indicates a combine sources including both shear and tensile components. The origin of earthquake swarms is still unclear. Nevertheless, we infer that the individual earthquake swarms in West Bohemia-Vogtland are mixture of the mainshock-aftershock sequences which correspond to step by step rupturing of one or a few asperities. The swarms occur on short fault segments with heterogeneous stress and strength, which may be affected by pressurized crustal fluids reducing normal component of the tectonic stress and lower friction. This way critically loaded faults are brought to failure and the swarm activity is driven by the differential local stress.

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Earthquake mechanism extended for rupture propagation estimate: West Bohemia/Vogtland swarm 2014

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The mechanism is an inherently point-source characteristics of an earthquake focus containing no information on the rupture propagation. The traditional description by the moment tensor offers little chance to absorb additional parameters related to finite-extent focus. Its alternative – the shear-tensile crack – is advantageously more flexible thanks to the fact that it is a physical model. It is the simplest extension of the traditional pure shear-slip model represented by complementing it with a phenomenon describing an opening or closing within the focal zone. This is achieved just by allowing a deviation of the slip off the fault plane. As extreme cases of the oblique slip, the model involves both the pure shear and the tensile crack. Technically, its advantage is a smaller number of parameters needed for its description: there are 5 parameters only, i.e. one parameter less than for an unconstrained moment tensor. Smaller number of parameters is an advantage in the inverse process, expressed in its greater robustness, which is important especially in sparse monitoring configurations. From this reason and thanks to a grid search approach to the inverse task, we can involve additional parameters to be optimized. The rupture velocity vector modifying the radiation pattern by the directivity effects is the first one at hand. We search for its direction constrained to lie within the fault plane marked by the mechanism, the ambiguity of the nodal planes being removed by constraining the fault plane close to the major tectonics in the area. The speed of the rupture is considered either fixed or free parameter. We apply the procedure to the data of the West Bohemia/Vogtland swarm in 2014, where an excellent configuration of the monitoring is available.

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2014 mainshock-aftershock sequences in West Bohemia/Vogtland as successors of previous swarms?

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The area of West Bohemia/Vogtland in western Eger Rift is typified by earthquake swarm activity with maximum magnitudes not exceeding ML 5. The seismicity is dominated by the area near Novy Kostel where earthquakes cluster along a narrow and steeply dipping focal zone of 8 km length that strikes about N-S in the depth range 7-11 km. Since 1992, earthquake swarms with several events exceeding magnitude level ML 3 took place in 2000, 2008 and 2011. The rate of activity of individual swarms increased with each subsequent swarm; the 2000 swarm being the slowest and the 2011 swarm the most rapid one. In 2014 the character of seismicity changed from a swarm-like to mainshock-aftershock character with three mainshocks occurred on May 24 (ML 3.6), May 31 (ML 4.5), and August 3 (ML 3.5). Succeeding aftershocks were by more than one magnitude level smaller and no foreshocks occurred, which differentiates this activity from the preceding swarms. Interestingly, the hypocenters of the mentioned earthquake swarms and mainshock-aftershock sequences share a common fault zone and overlap significantly.

Analysis for the investigated period further shows that seismicity at lower magnitude levels has changed from swarm-like to a mainshock-aftershock character in 2014. We find that the swarms can be interpreted as a set of overlapping aftershock sequences with Omori-like decay with p=1, which is similar to the decay of the 2014 sequences. ETAS analysis gives the lowest number of background events in 2014 compared to higher levels in 2000-2011 swarms showing that the 2014 sequences were preferentially driven by stress transfer. Our results show that the behavior of the same segment of the fault plane changes in time producing either earthquake swarms or mainshock-aftershock activity.

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2014 earthquake sequence in West Bohemia/Vogtland responsible for the sudden increase of CO2 flow rate?

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Geodynamic activity in West Bohemia/Vogtland is demonstrated by M4+ earthquake swarms and degassing of deep-generated CO2 of upper mantle origin. The migration patterns of seismicity, Coulomb stress analyses and related numerical models suggest that pressurized fluids act as triggering force of the earthquake swarms. In the period May-August 2014 three M3.5 – M4.5 mainshocks followed by aftershock sequences occurred in the area. CO2 degassing rate is being monitored on three mofettes in the area. The record at Hartoušov mofette shows a transient change of trend of the CO2 flow related to the earthquake activity. Since the start of the monitoring in November 2009 a steady decrease of flow from 40 to 6 l/min in May 2014 took place, however staring on 24 May 2014, which was the time of the first mainshock, a rapid increase of flow rate has been observed, which lasted until mid July reaching more than 30 l/min. The fast propagation of the pressure pulse to the surface points to high permeability of the CO2 feeding channel, however, on the contrary, the long rise time of the flow rate indicates rather slow response of the intermediate crust properties to swarm activity.

We use numerical modeling of fluid flow in porous media to test if the slow decrease of CO2 flow in past years and its rapid increase after the first mainshock could be interpreted in terms of the fluid-valve model. We find that layered models of the crust with substantial different diffusivities are capable to explain the observed surface variations of CO2-flow.

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IUGG-5447

Tectonic tremors in Taiwan: Summary and outlook

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Taiwan is a young collisional orogenic zone that presents a special case in tremor study, in which the tremors observed here seem not to be directly associated with processes at plate interface. Tremors in Taiwan are first discovered as triggered events by distant large earthquakes. Further investigation detects the presence of ambient tremors underneath the southern Central Range, a region characterized by high heat flow, large geothermal gradient, and strong seismic attenuation. The tremors appear to cluster in a confined region at crustal depths, without following any certain structure, such as fault plane near which subduction zone and transform fault tremors concentrate. The duration of Taiwan tremors observed so far is several to tens of minutes, shorter than that of subduction zone tremors. Tremor activity here closely correlates with coseismic stress change due to local major earthquakes, and with normal faulting earthquake swarms also present in the tremor-prone area but at shallower depths. Despite much progress made to date, difficulties in identifying more tremor signals due to high noise level and sparse seismic receiver coverage hinder solutions to critical questions such as conclusive tremor depth distribution, focal mechanism, and whether tremors migrate. To answer these questions, a new field campaign is currently underway to deploy a dense broadband seismic array along the ridge of the southern Central Range, directly above the tremor source region. The new array is able to detect tremors even in the noisier daytime, thus a comprehensive tremor catalog can be built. Near vertical incidence of tremor signals offers potential for determining focal mechanism and migration pattern, enabling further exploration of the origin of tremors in Taiwan.

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Low frequency seismic swarms and tectonic tremors in China continent seismological observation

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Low frequency seismic swarms and tectonic tremors, is usually refers to the seismological observations of a weak seismic signals, have a few minutes to a few weeks duration and a frequency domain from 0.01Hz to 5Hz (a period domain 0.2~100s), and lacking the higher-frequency energy radiated by common earthquakes. In this paper, we applied a continuous waveform data of the continent seismological stations in China, focuses on analyzing the low frequency seismic events and tectonic tremors hidden in the data, and study its space-time distribution and spectrum characteristics. The preliminary researches show that the low frequency seismic events and tectonic tremors can also be observed by the continent seismological stations in China, with multiple period and frequency components of 30s, 60s, 100s and 2~8Hz etc.. And the duration of the seismic sequences can be up to several hours, and has obviously periodic variation characteristics. Before Wenchuan 8.0 earthquake on May 20, 2008 and Lushan 7.0 earthquake on April 20, 2013 occurred, the observed low frequency seismic swarms and tectonic tremors are obviously different. Among them, the signal of high frequency composition for Wenchuan earthquake is rich, with a frequency domain 2~10Hz. But the signal of high frequency composition for Lushan earthquake is relatively single, a frequency domain is concentrated in the range of 2~3Hz.

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The swarm characteristics in Shanxi rift and its application forecast research

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Due to its intensity and frequency of earthquake swarms in this region, the Shanxi rift is presently identified as one of the most active tectonic regions in North China. Since the beginning of earthquake observation system in 1965, more than 6000 small to moderate earthquakes have been detected in this region, and half of them are belong to 89 clusters (hereinafter described it as swarms). Thus, study on the characteristics of the seismic swarms in the Shanxi rift is of strong importance on understanding the tectonic activity in this region.

In the work, we collected catalogs for the period before and after the earthquakes which have swarm aftershock sequences, then constructed EQT or WKF catalogue files for time-spatial analysis. Two characteristics can be outlined from the results: 1) most of the swarms occurred in the central graben basins and the rest sporadically distributed in the peripheral mountains. And the temporal intervals of swarms are unevenly in the recent decades, swarms with $M_L > 4.0$ occurred frequently before the Ms 5.6 Datong-yanggao earthquake occurred on Nov. 1 ,1999, and experienced an unprecedented active period between 1966-1977.However, since 2002 no swarms wih $M_L > 4.0$ ever occurred until today, thus, the swarm activity is reduced since then. 2) Based on the calculated distribution and interval between the earthquakes and the potential swarms among all of the swarms, 50 of them exhibit precursory characteristics. This feature provides us an important clue for evaluating potential seismic hazard in North China.

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Variation of the Earth tide-seismicity compliance parameter for the west site of the Aegean Volcanic Arc, Greece

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The results of the analysis of the last 50 years earthquakes series in seismic active areas of Greece, i.e. the areas (a) of the Mygdonian Basin, (b) of the Ionian Islands and (c) of the Hellenic Arc, indicate that the monthly variation of the frequencies of earthquake occurrence is in accordance with the period of the tidal lunar monthly and semi-monthly (Mm and Mf), diurnal luni-solar (K1, O1) and semidiurnal lunar (M2) and solar (S2) tidal variations. In addition the confidence level for the identification of such period accordance between earthquakes occurrence frequency and tidal periods varies with seismic activity, i.e. the higher confidence level corresponds to periods with stronger seismic activity. These results are in favor of a tidal triggering process on earthquakes when the stress in the focal area is near the critical level. Based on these results, we consider the confidence level of earthquake frequency of occurrence - tidal period accordance, p, as an index of tectonic stress criticality for earthquake occurrence. A test on posterior of this idea, (i.e. the value of the confidence level index, p, indicate the fault matureness) in the case of the recent seismic activity at Fthiotida, and Evoikos was positive. In this paper we present the results of a third test by the occasion of the recent seismic activity of the west site of the Aegean Volcanic Arc. The results also are positive. We suggest that this compliance parameter may be used as an additional element for the seismic risk assessment.

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Time reverse stacking of the West-Bohemia earthquakes: Modelling of rupture process

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We performed a series of tests on synthetic as well as real data in order to assess the capability of the time reverse stacking method for determining rupture parameters of micro-earthquakes recorded by local networks of seismic stations. We constructed a dense subsurface grid of candidate point sources and calculated travel times for each pair of a grid point and a seismic station. We shifted waveforms back in time and stacked them over all stations. The time-space dependence of the calculated brightness function was analysed in order to estimate parameters of the rupture process. The method was applied to selected M3+ earthquakes of the 2008 West-Bohemia earthquake swarm, Czech Republic. The earthquakes were recorded by the West Bohemia Network (WEBNET) stations with a sampling rate of 250 Hz. The results of the time reverse stacking method are compared with those obtained using the analysis of directivity of the P and S waves. We employ three finite-source models: the linear unilateral model, the linear symmetrical bilateral model and the circular fault model, and discuss which of them is mostly consistent with observations.

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Approaching moment tensor inversion and Q factor tomography of Western Bohemia earthquake swarms

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Western Bohemia shows frequent earthquake swarm activity characterized by very confined source regions. The majority (80%) of the seismicity nucleates in the area beneath Novy Kostel in the Czech Republic. While most earthquakes are weak, with magnitudes M_L<3.5, few largest events reached magnitudes up to M_L=4.6 in recent years. The seismic activity can hypothetically be related to migrating magmatic fluids or gases of magmatic nature. Both hypothesis are supported by the imaging of a compact and potentially impermeable body at the top of the seismogenic zone. This could act as a sealing layer preventing further migration of uprising fluids. This scenario suggests that fluids gathered beneath the sealing layer could increase the pore pressure and eventually cause fracturing in the seismic swarm focal region.

The origin of the seismic swarms remains debated but further insights can be drawn from the analysis of focal mechanisms of weak events. A semi-automated full waveform based inversion routine is set up to identify moment tensors of an earthquake swarm which occurred in 2008. The applied method uses pre-calculated Green's function databases. This allows to invert for numerous moment tensors while keeping computation time low. The data used for analysis was recorded by the West Bohemia seismic monitoring network (WEBNET).

The preliminary focal mechanism solutions serve as input for a master-slave-event method which is currently under development. This method aims at evaluating attenuation properties of the seismogenic region by means of a spectral analysis of event couples. As gas and fluid content have a major impact on the attenuation of seismic waves, attenuation tomography can be helpful to discriminate the origin of the seismicity in the focal region.

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WEBNET versus REYKJANET: Comparing two local monitoring networks and results of data interpretation

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Institute of Geophysics ASCR, Czech Rep., operates two local monitoring networks: WEBNET (WEstern Bohemia NETwork) and REYKJANET (Reykjanes peninsula, South-West of Iceland). Both networks are similar as regards their instrumentation and the range of station coverage. While WEBNET has been operated for more than 25 years, REYKJANET started in 2013 and, now the first 1-year of data overlap gave us the opportunity to compare selected results of interpretation of both data sets. However the object of monitoring is the same - earthquake swarms. We show quantitative differences in magnitudes, depth distribution and hypocenters clustering. We have also tested and evaluated two kinds of phase picking (manual and automated) and localization procedures (absolute and 'double-difference' localizations). We propose ways how to efficiently process recorded data. Finally, 3-D tomographic images corresponding to the geological medium were calculated using the same software and algorithms but yielding different results. The relations between the tomographic velocity model and geological building are also discussed.

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Wadati method as a simple tool to study seismically active fault zones: A case study from the West-Bohemia/Vogtland region

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The ratio of P- to S-wave velocities,VP VS , is an important parameter characterising rock composition and fluid saturation. We have studied some properties of the ratio in the West- Bohemian seismically active region, using data from the earthquake swarm which occurred there in 2008. The earthquake swarm was well recorded by 23 seismic stations from epicentral distances less than 25 km. We selected a subset of 158 events with local magnitudes between 1.5 and 3.8. Applying the Wadati method to the measured arrival times of P and S waves, we arrived at an average value of VP/VS =1.68 ± 0.01. This differs a little from the value of VP/VS =1.70 , which is routinely used for earthquake locations in the region at present. Moreover, it was recognized that the points in the Wadati graphs for some stations were systematically deviated from the mean straight lines. In particular, the stations with the largest positive deviations (above the mean straight lines) are situated close to the Mariánské Lázne Fault and to some intensive mofettes. Further analyses revealed reduced Pand S-wave velocities along the seismic rays toward these anomalous stations. In our opinion, the seismic waves arriving at the anomalous stations probably propagated along a fault or another zone of weakness. In this way, our results support the hypothesis that the Mariánské Lázne Fault is a deep-seated fault continuing down to the seismically active zone of local earthquakes. From a general point of view, this study demonstrates that even some narrow structural anomalies in the crust, such as fault zones, can be recognized by the simple Wadati method if data from a dense seismic network are available.

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Automatic event detection using artificial neural networks – application to swarms in West Bohemia

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The proposed algorithm was developed to be used for Webnet, a local seismic network in West Bohemia. The Webnet network was built for seismic monitoring of West Bohemia/Vogtland swarm area. During the earthquake swarms there is a large number of events which must be evaluated automatically to get a quick estimate of the current earthquake activity. Our focus is to get good automatic results prior to precise manual processing. With automatic data processing we may also reach a lower completeness magnitude.
The first step of automatic seismic data processing is the detection of events. To get a good detection performance we require low number of false detections as well as high number of correctly detected events.
We used a single layer recurrent neural network trained by manual detections from swarms in West Bohemia in the past years. As inputs of the single layer recurrent neural network we use STA/LTA of half-octave filter bank fed by vertical and horizontal components of seismograms. All stations were trained together to obtain the same network with the same neuron weights. We tried several architectures - different number of neurons - and different starting points for training. Networks giving best results for training set must not be the optimal ones for unknown waveforms. Therefore we test each network on test set from different swarm (but still with similar characteristics, i.e. location, focal mechanisms, magnitude range).
We also apply a coincidence verification for each event. It means that we can lower the number of false detections by rejecting events on one station only and force to declare an event on all stations in the network by coincidence on two or more stations.

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Cluster analysis of earthquake swarms - results from West Bohemia/Vogtland and South-West Iceland

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We explore behavior of earthquake swarms in different tectonic basis in order to understand why the energy is released by sequences of small events and not by mainshocks and aftershocks. We use catalog data from West Bohemia/Vogtland (WB) situated within a tectonic plate, and three different tectonic basis in South-West Iceland (SWI), namely boundary of tectonic plates (Krísuvík), the edge of a mainshock-aftershock-like zone (Olfus, South Iceland Sesmic Zone) and the volcanic area (Hengill). In case of WB we analyze two swarms, 2000 and 2008, located on the same fault segments. We analyze distribution of events based on spatial metric obtained from double-difference locations and time metric (in case of WB and SWI), and a focal mechanism metric based on double couple (DC) solutions (in case of WB). For this purpose we use clustering method developed by S. Cesca. In each area, the location- and time-based analysis discloses several separate clusters. One significant and several smaller location-based clusters appear. The time phases are characterized by abrupt increase of activity in a view of number of events and their magnitude. In both 2000 and 2008 WB-swarms the DC-based analysis reveals three main mechanisms (oblique-normal, oblique-thrust and thrust faulting), and one additional in the 2008 case (thrust faulting with different strike). Strikes and dips correspond to geometry of segments identified by the location-based clustering. The main segment is characterized by the most frequent mechanism (oblique-normal), however, several significantly different ones are also presented inside the segment. All the results support an idea that earthquake swarms activate a number of smaller fault segments with heterogeneous stress rather than one main fault.

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Optimizing an array-network geometry to improve the monitoring of crustal earthquake swarms

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Earthquake swarms (ES) are represented by an immense number of weak events that occur in a spatio-temporal cluster over a period of weeks or months, and are not associated with a typical mainshock-aftershock sequence of an earthquake. Although ES are mainly connected to volcanic activities, they are also observed in non-volcanic areas, as in the NW Bohemia/Vogtland area.
The precise analysis of such a high rate activity is crucial to study the underlying process. However, relying just on the network monitoring with routine automatic procedures is insufficient to detect all small events. To detect and distinguish sequences of small events, arrays are superior to networks; because arrays waveform stacking increases SNR, enables separation of coherent waves of different slownesses, and consequently lowers the detection threshold. Though, event back azimuths may be poorly determined by source location based on a single array.
To improve seismic monitoring of local swarm activities, we suggest a combined processing of a network with small aperture arrays. In this case arrays increase the event detection and separation capability, while high quality network recordings of detected events reduce the azimuthal error of location.
We introduce a search method to define an optimum position of an array which can improve the overall performance of an existing network. A cost function based on the overall hypocentral error of a synthetic swarm is minimized in a optimization process. To predict hypocenter errors a joined network-array waveform stacking method is used. A synthetic model of ES in the NW Bohemia/Vogtland area and current stations of WEBNET are used as input parameters. We discuss different possible locations and geometries for future array installations in NW Bohemia.

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Aseismic transient driving the swarm-like seismic sequence in the Pollino range, Southern Italy

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Swarm-like seismic sequences requires understanding of the underlying driving mechanims to link observations to the spatio-temporal evolution of events. The transient nature of the driving mechanisms may vary ranging from transient aseismic slip to diffusion or redistribution of pore pressure. Distinguishing among such forcing mechanisms may be critical to evaluate the hazard due to seismic swarms. Here we study the ongoing Pollino range (Southern Italy) seismic swarm. The two largest shocks of M_w=4.2 and M_w=5.1, are among the largest recorded in the Pollino area, a seismic gap in the Italian peninsula. We investigate the geometrical and mechanical characteristics of the largest earthquakes and of the entire swarm. We calculate the focal mechanisms for M>3 events and the Coulomb stress on nearby known faults and analyse statistically the earthquake catalog. We characterized the temporal evolution of the swarm by investigating the statistics of frequency-size distribution, interevent times and the transient forcing through ETAS-based modeling. We find that 25% of the earthquakes in the sequence can be explained as afetrshocks, and the remaining 75% may be attributed to this transient forcing. The b-values change in time throughout the sequence, with low b-values correlated with the period of highest rate of activity and with the occurrence of the largest shock. We identify two scenarios consistent with the observations and our analysis: This and past seismic swarms may have been 'passive' features, with small fault patches failing on largely locked faults, or may have been accompanied by an 'active', largely aseismic, release of a large portion of the accumulated tectonic strain. Those scenarios have very different implications for the seismic hazard of the area.

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Identifying earthquake swarms off the coast of Malta (Sicily Channel)

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Current monitoring of the Sicily Channel seismicity, between Sicily, Malta and Libya, shows that the area is characterised by low-to-medium magnitude ($M < 4.5$) earthquakes. Many of them occur as seismic swarms that typically last for a few days. These swarms are being identified during the on-going compilation of a comprehensive, two-decade long, seismic catalogue for the territory of Malta, put together by the Seismic Monitoring and Research Unit at the University of Malta. Many earthquakes are recorded only on one seismic station and located using a single-station method. Several events, however, are also recorded on other neighbouring seismic stations, and better located using standard procedures.

In the present work we show the locations of the identified earthquake swarms and their respective sequence over time. We relocated them and for some of the most energetic events we computed the moment tensor solutions, obtaining the focal mechanisms, source depths and moment magnitudes determined through a grid search technique. The results are interpreted in terms of the likely geodynamic situation of the study area. Furthermore, the data set will be used to compile a relationship between moment and local magnitude. The complete seismic catalogue will contribute to new constraints on the regional tectonics and the local seismic hazard, and provide a rich database for future seismological analysis.

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Rupture propagation estimate from second-degree moments: application to 2014 earthquake swarm in West Bohemia/Vogtland

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Second degree moments allow estimating “non-point” characteristics of a seismic source within the point source approximation, thus providing coarse view “inside” the focus. They complement the standard moment tensor, which describes the mechanism of the earthquake focus viewed as a point. By using second degree moments we can assess basic features of the finite extent source as integral characteristics of the focus advantageously without a costly slip-distribution modeling, for which often there are not enough data available.
Second-degree expansion adds 14 new source parameters into the relation between seismic observations and the source in addition to 6 components of the moment tensor. While the latter describe the mechanism only, the former allow derive information on the position and time of the major seismic energy release (spatial and temporal centroids), geometry of the focus (source ellipsoid), duration of the source process and the rupture propagation (rupture velocity vector). We invert full waveform data in an iterative way for the mechanism and for the second-degree moments. To see the finite-extent features of the focus, we need to work with frequencies beyond the corner frequency of the event.
We apply the method to the earthquake swarm data from West Bohemia/Vogtland on the border between the Czech Republic and Germany. Seismic activity occurs in earthquake swarms with magnitude not exceeding 5. The Webnet network consists of 23 stations well distributed around the Nový Kostel locality. The last strong swarm occurred in 2014. We process the data from well-recorded events in terms of the second-degree moments, compare the mechanism with previous studies and interpret the indication on the rupture propagation in terms of the current knowledge about the area.

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Precise tremor source locations in southern Taiwan

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Triggered and ambient tectonic tremor has been observed in the Island of Taiwan, an arc-continental type collision environment. Different from regular earthquakes, deep tremor is difficult to locate across a seismic network due to its non-impulsive, low-amplitude property, especially for depth constraint. We use the stacked vertical and horizontal seismograms of a small-aperture array close to the tremor source in the southern Central Range, with three three-component and tens of vertical component short-period seismic stations, to enhance the signal-to-noise ratio. We select the strong tremor events with a steep incidence angle to the array, and cross correlate the vertical and horizontal seismograms to measure the lag time between the compressional and shear waves (S-P time). Then we combine the S-P times with slowness determined by array analysis to largely reduce the depth uncertainty (±6 km) achieved by the conventional tremor location techniques, using differential S-wave arrivals from tremor envelopes. Because most recent studies have shown that tremor activity mainly distribute along major fault interface and below the seismogenic zone where regular earthquakes occur, this study of precise tremor source locations can help to better understand fault mechanics at the bottom of the seismogenic layer in the collision environment.

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Long-term ocean bottom monitoring for shallow slow earthquakes in the Hyuga-nada, western part of the Nankai Trough

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The Hyuga-nada region, nearby the western end of the Nankai trough in Japan, is one of the most active areas of shallow slow earthquakes in the world. Recently, ocean-bottom observation of offshore seismicity near the trench have succeeded to detect shallow tremor as a complete episode lasting for one month exhibiting similar migration property of deep tremor for the first time [Yamashita et al., in revision]. This activity was also associated with shallow very-low-frequency earthquake (VLFE) activity documented by land-based broadband seismic network. The coincidence between tremor and VLFE and their migration pattern show strong resemblance with deep tremors during ETS episodes; this similarity suggests that the tremor activity in the shallow plate boundary may also be coupled with VLF and short-term slow slip events (SSEs) in this area. However, the shallow SSEs have not been detected to date. To clarify the relationship among these slow earthquakes is important to improve the assessments of the potential of tsunamigenic megathrust earthquake. Motivated by these issues, we started long-term ocean-bottom monitoring in this area from May 2014 using 3 broadband and 7 short-period seismometers, and 3 pressure gauges for covering geodetic period range in order to detect the suspected shallow SSE. In January 2015, we replaced the instruments and obtained the first data which includes minor shallow tremor and VLFE activity on June 1-3, 2014. Preliminary results of data analysis show that the shallow tremor activity occurred at the same area of the 2013 activity, but clear tremor migration has not been found yet. However, it is promising to detect the large short-term SSE with our dense and long-term observation including with pressure gauges in near future.

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Vp/Vs ratio variations in the source region of West Bohemian earthquake swarms

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Seismic activity in the West Bohemia expresses itself in the form of a so called earthquake swarms. During these swarm periods thousands of events occur during weeks to months within a small focal area.

In this study we have estimated the V_p/V_s ratios within the focal area using the double difference methods – Lin and Shearer (2007) and Dahm and Fischer (2013). These methods allow us to estimate the velocity ratio by measuring the delay times between the earthquakes P and S arrivals. To ensure the correct delay time estimation we used waveform cross-correlation techniques instead of catalog readings.

We applied these methods to 2011 swarm (M_L up to 3.5) and 2014 mainshock - aftershock sequences (M_L up to 4.5). Preliminary results show decrease of the velocity ratio in the beginning phase of the activity and its recovery after. Similar behavior has been observed by Dahm and Fischer (2013) during the 1997, 2000 and 2008 swarms and has been interpreted in terms of Biot - Gassman equations, assuming the presence of the over-saturated fluids degassing through the focal area during the initial phase of the earthquake activity.

Dahm, T., and Fischer, T., 2013. Velocity ratio variations in the source region of earthquake swarms in NW Bohemia obtained from arrival time double-differences. Geophys. J. Int. 196, 957-970.

Lin, G., Shearer, P. M. 2009. Evidence for water-filled cracks in earthquake source regions. Geophys.Res. Lett. 36, L17315, doi:10.1029/2009GL039098.

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Rupture parameters of three ML 3.5 - 4.5 mainshocks occurred in 2014 in West Bohemia/Vogtland determined by different methods

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Three earthquake sequences took place in the Nový Kostel focal zone in West Bohemia/Vogtland in 2014, each of them initiated by mainshock. Precise relative locations of the sequences show that the mutual distance of the ML 3.5, 4.5 and 3.6 mainshock hypocenters is below 500m, which indicates partial overlap of the ruptures. Besides, lack of aftershocks is observed in the vicinity of the mainshock hypocenters, which allows for delineating the mainshock rupture area. We apply three independent methods to determine the rupture area of the mainshocks using data from the WEBNET network. First, displacement spectra corrected for attenuation were used for determining the corner frequency and rupture radius based on the circular source model. Second, based on precise relative locations, we analysed the spatial distribution of early aftershocks in order to delineate the rupture edge and corresponding rupture radius. Both these methods give similar results consistent with rather high static stress drop of about 100 MPa. Finally we performed full waveform inversion of the three events using local stations in the frequency range 0.2- 3Hz with the use of a single or multiple point sources in order to study possible source complexities and/or non-double-couple components.

IASPEI (Seismology, Geophysics)

S01ba - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

IUGG-0651

Consistent phase picking for high-resolution body wave tomography in Montenegro and vicinity

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High-resolution P- and S-wave velocities models provide essential information on lithosphere structure and, consequently, on seismotectonic potential. In order to obtain uniformly high ray-coverage appropriate for performing local earthquake tomography of Montenegro and vicinity, data were compiled from 11 national and regional seismic networks. This extensive data set comprises waveforms from around 1500 earthquakes digitally recorded at more that one hundred stations in the region. The waveform data formats, quality of catalogues and archived data differ significantly between networks. The establishment of a harmonized database included implementation of several procedures: data merging according to the event catalogue, identifying and dismissing bad data, converting data from different formats to miniseed, etc.

For the purpose of developing minimum 1D models for high-quality earthquake location and as initial reference model for subsequent 3D tomography, a consistent quality assessment of P- and S-wave arrival times and consistent phase identification has to be achieved. The creation of a high-quality data set for local earthquake tomography required the P- and S- phases re-picking, on original seismograms. Procedures for consistent routine picking, including seismic phase interpretation and timing quality assessment, were applied to produce a high-quality data set of several thousands of P- and S-phase picks. This data set is used for calculation of the P- and S- minimum 1D models, through the iterative inversion procedure using VELEST software.

The resulting minimum 1D models will be used as appropriate velocity models for uniformly high-precision routine earthquake location in the region and, subsequently, also as the initial reference model for 3D tomography.

IASPEI (Seismology, Geophysics)

S01ba - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

IUGG-1844

Anomalous long-period later phase developed by seawater during the 2005 off-Tohoku outer-rise earthquake

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We found an anomalously large, long period later phase during an outer-rise earthquake (M7) occurring off-Tohoku by analyzing dense broadband records derived by applying a digital filter to the Hi-net short-period records. This later phase was appeared ~100 s after the Rayleigh wave packet widely over eastern Japan and the amplitude was comparable to the Rayleigh wave in displacement recode. Dominant period of the phase was T=13~14 s and particle motion showed a retrograde motion like a Rayleigh wave. To investigate the developing mechanism of the phase, we performed numerical simulations of seismic wave propagation in 3D heterogeneous structure by means of a finite difference method. To reproduce the observed characteristics of the phase, we examined the effects of topography, bathymetry, seawater layer and subducting oceanic plates in the simulation. The result demonstrated clearly that the phase was originated from an oceanic mode Rayleigh wave which was firstly spreading slowly (~1 km/s) in deep sea area (~6 km depth) and then converted into an ordinary Rayleigh wave (~3 km/s) propagating on land at the seafloor slope between trench and ashore. Because of the slow speed of the oceanic Rayleigh wave in deep sea area, the converted Rayleigh wave was delayed and separated from the main packet of preceding Rayleigh wave and appeared on land as a large-amplitude later phase. This result indicated that the Rayleigh wave propagation in the sea area is completely different from that on land. Therefore, it is important to consider the seawater layer properly in the simulation to estimate properly the long-period ground motions developed from offshore earthquakes.

IASPEI (Seismology, Geophysics)

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IUGG-2512

ALGORITHM FOR CALCULATING THE SEISMIC MOMENT TENSOR OF STRONG EARTHQUAKES OF AZERBAIJAN FOR THE PERIOD 2012-2014 YY.

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The present level of research of deformation processes of the crust of Azerbaijan is impossible without information about working in her fields of tectonic stresses. Data about the fields of stress and strain, together with data about neotectonic and contemporary motions of the geological, structural-tectonic structure, as well as data on existing physical fields in the lithosphere allow properly solve the problem of creating models of deformation of large tectonic structures of the earth's crust. The aim of this study is to process, organize, interpretation and synthesis of seismic materials on mechanisms of earthquake records based on modern digital stations and the use of the newly developed algorithms and softwares.
For this work algorithm was used by the method of inversion of waveforms - TDMT INVC, developed by D. Dreger from the University of California, Berkeley. This package is used to calculate how the seismic moment tensor, and Mw.
On the basis of a joint analysis of focal mechanisms of earthquakes recorded in the Greater Caucasus is composed geodynamic model of the region under study. The result of the stress distribution and the corresponding shifts in the system of longitudinal and transverse faults is twisting the individual blocks in the clockwise and counterclockwise, and the horizontal movement of blocks Kura River valley to the north (subduction) and blocks the surface structure of the Greater Caucasus to the south (thrust). Due to the formation and development in the Kura Basin large crustal fault-reset-Caucasian direction (fault separation and transport), there is subducting under the structure of the Kura depression Greater Caucasus structure that enhances the convergence Greater and Lesser Caucasus.

IASPEI (Seismology, Geophysics)

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IUGG-4070

Automatic event detection in Southwest Iceland using seismic migration in a three dimensional velocity model

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With continuous recording of data and rapidly growing data storage capacities in recent years, the need for automatic procedures for data evaluation has increased. In the Hengill volcanic area, part of the rift zone in Southwest Iceland, the presence of both high natural seismic activity and seismicity induced from the exploitation of geothermal power confirms the case. As part of a local earthquake tomography study, data from 4 years (2009-2013) recorded by 25 stations within an area of approximately 50 x 50 km is evaluated. In order to automate and speed up the process of event detection/location and subsequent phase picking, we start by back-propagating signal to noise attributes in a 3D time field. A local maximum of stacked amplitude in time and space will trigger the detection of an event. This method is fully automatic, and allows the detecting of low amplitude events, events that may be skipped by common detection procedures relying on automatic phase picks. Detecting small events is related to the number of false alarms one is willing to accept (e.g. local noise bursts, real events only visible on one station, etc.). Most false alarms can be discarded using logical selection criteria. Furthermore, the found event origin parameters are used to induce a focused search of the three component seismic traces for P- (and S-) phase picks. We have applied the automatic detection method to a subset of data, comparing the use of a 3D against a 1D velocity model and stacking two or three components per station. The migration based detection finds more than the catalogued events from the permanent, locally sparse, SIL network.

IASPEI (Seismology, Geophysics)

S01ba - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

IUGG-5271

Earthquake ground truth location from ambient seismic noise and its implication for testing accuracy of 3D earth models

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Comparing ground truth location and the earthquake location inverted with 3D earth models is one of the straightforward ways for validating accuracy of 3D velocity models. Ground truth location are usually based on man-made explosions or earthquakes recorded with dense seismic network. Recently, the discovery of estimated Green’s function (EGF) from ambient seismic noise has made possible a new approach for achieving ground truth location of earthquakes. In the new location method, the continuous noise waveform record of a nearby seismic station (the virtue event, usually within dozens of km from an earthquake) is correlated with noise data at remote stations, and the surface waves in EGF are compared to earthquake surface waves to get relative location between the virtue event and the earthquake. As location of the virtue event is accurately known, the relative location of the earthquake is actually ground truth location (absolute location). Via comparing the location of a few shallow moderate earthquakes observed with INSAR, it is found that the earthquake location from ambient seismic noise is within 3km when remote stations are around 1000 km, and within 2km when the remote stations are within 300km. We will establish a database of earthquake ground truth location with the ambient seismic noise method, and assess accuracy of 3D earth models with the new database.

IASPEI (Seismology, Geophysics)

S01bb - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

IUGG-1693

A data-comprehensive seismic Earth model across the scales

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We present the current state of the ‘Comprehensive Earth Model’ (CEM), a 3D visco-elastic multiscale global Earth model. The purpose of this project is to represent the Earth on all seismologically accessible scales; to present high-resolution sub-models where data and theory allow, and to present a low wavenumber Earth in regions that have yet to be probed in detail. To accomplish this, we have designed the model to be independent of any particular forward solver. This allows a variety of forward and inverse techniques to be used, each of which may contribute updates within its particular regime of validity. The CEM aims to be a community platform for seismological research and structural interpretation. With this in mind, we report on technical aspects regarding the CEM workflow, with the hope of fostering collaboration on interesting and novel regional updates.

In its initial form, the CEM consisted of the smooth 3D global S-wave velocity model S20RTS, added to a modified version of PREM. Superimposed on this background were four high resolution subregions imaged through full waveform tomography: Australia, Japan, the South Atlantic, and Europe. Over the past year, full waveform updates have been contributed to Europe and Japan, along with a traveltime update sensitive to the deep structure of Europe. As well, an iteration of a global scale full waveform inversion, using a dataset designed to validate the quality of future regional updates, has been completed. With this update applied, we discuss the initial results from a full waveform tomography aimed at resolving the deep structure beneath the African continent.

IASPEI (Seismology, Geophysics)

S01bb - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

IUGG-2369

Alternatives for computing seismic body-wave travel times using a 3-dimensional model

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We compare applicability, computational costs, and travel time accuracy for a global 3D model and ray tracer (LLNL-G3D, LLNL-Earth3D) and a computationally efficient Region Seismic Travel Time (RSTT) method. Both models and travel time codes are openly available. LLNL-G3D is a whole-earth 3D model of P-wave and S-wave seismic velocity, and the multi-threaded LLNL-Earth3D code can be used to compute travel times for first-arriving P-waves and S-waves, surface reflections (e.g. pP,SS), reflections off of velocity discontinuities (e.g. PcP), crustal phases (e.g. Pg and Lg) and core phases (e.g. PKP). RSTT is a model and method for computing travel times for regional phases (Pn, Pg, Sn, and Lg), whose travel times deviate most from commonly used, radially symmetric models. The RSTT model includes a 3-dimensional crust and laterally varying P- and S-wave velocity in the mantle. Mantle velocity is parameterized as a linear function of depth, which enables millisecond computation on a single processor. Travel time computation for LLNL-Earth3D is typically 0.1 second, but can require 1 second for some regional phases. For LLNL-G3D/Earth3D, prediction uncertainty for first-arriving P-waves is approximately 0.5 seconds at teleseismic distances and between 0.5 and 1.0 second at regional distances. For RSTT, uncertainty for Pn predictions is between 0.8 and 1.2 seconds. We conclude that LLNL-G3D provides superior travel time prediction accuracy for all phases used in seismic location. However, RSTT is a good alternative for real-time monitoring systems when pre-computation of travel times is impractical. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

IASPEI (Seismology, Geophysics)

S01bb - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

IUGG-2429

3D Model of Iran from seismic and gravity observations

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We present a 3D seismic velocity model of the Iran region generated using a joint inversion simultaneously fitting body wave travel time measurements and high-wavenumber filtered Bouguer gravity observations. The body wave data set is derived from previous work on location calibration and includes a large (>1000 events) subset of events that qualify as GT5. The associated arrival time data sets for these events include many readings of direct crustal P and S phases, as well as regional (Pn and Sn) and teleseismic phases. The data set has been carefully groomed to identify and remove outlier readings and empirical reading errors are estimated for most arrivals from a multiple event relocation analysis. We use gravity anomalies derived from the global gravity model Earth Gravitational Model EGM2008. To avoid mapping broad, possibly dynamically caused features in the gravity field into density and seismic speed variations, we high-pass wavenumber filter the surface-gravity measurements. We use a simple, approximate relationship between density and seismic velocities so that both data sets may be combined in a single inversion. The final optimized 3D models allow us to explore the relevant question of “Can multi-parameter tomography address crustal heterogeneities and areas of limited coverage, and improve travel time predictions?”. Our large data set of earthquakes with calibrated locations is especially suitable for such an investigation. Final results of the simultaneous inversion will also help us to better understand one of the most prominent examples of continental collision.

IASPEI (Seismology, Geophysics)

S01bb - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

IUGG-4618

Global 3-D tomographic imaging of the crust and mantle for enhanced seismic monitoring

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Global-scale tomographic images of the Earth's seismic velocity structure provide key insights into the state and evolution of our planet, and thus the development of such models has been a mainstay in solid Earth geophysics research for more than three decades. Because of their predictive abilities, global-scale 3-D images are also capable of enhancing monitoring applications including accurate seismic event locations based on 3-D travel time predictions. We have constructed new images of the crust and mantle using novel data processing and imaging techniques developed over the past several years. The new techniques include 3-D ray-tracing with multipath considerations, global multiple event location algorithms, and multi-resolution imaging within a spherical tessellation model framework. The most recent model is a jointly derived model of shear and compressional wave speeds based on a large suite of P- and S-wave phases. The images reveal new details and more focused structures within the Earth, providing clear evidence that these new global-scale models and techniques represent advancements in global seismic tomography. Validation tests demonstrate that these global-scale models reduce the median event location error by 40-70% (relative to a 1-D model) for a suite of 116 validation events with well-constrained true locations. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-ABS-666015

IASPEI (Seismology, Geophysics)

S01bp - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

S01bp-317

The 3D-strain tensor analysis of seismic deformations in Turkey using GPS velocity field (RTK-CORS Network)

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This study describes and maps the geographic distribution of the normal and shear strains using the Turkish Real Time Kinematics-Continuously Operating Reference Stations Network (RTK-CORSNetwork). We analyze the strains with respect to thegeodetic CORS Network and estimate the horizontal/vertical components of strain tensors using velocity vectors of CORS for the whole surface of Turkey. We used the observations from CORS to estimate the strain tensors and to monitor the crustal deformations resulting in the displacements on the points and utilized the Delaunay Triangulation model. The strain tensors were separately computed for each triangle utilizing the coordinates and velocity vectors of CORS. We transformed the computed strain tensors to the local coordinate system to obtain the horizontal/vertical components of the strain tensors. We carried out an appropriate surface bi-harmonic and polynomial interpolation method using the strain elements to obtain a strain model for the complete surface and to illustrate the strain component maps. The normal and shear strain variations along the x, y, zaxes and the xy, xz, yzplanes, respectively, show that vertical displacements are quite effective on the tectonic processes. The main deformational component is the shear strain on the yzplane that determines the faulting mechanisms in Turkey. The normal strain along the y-axis and horizontal shear strain on the xy-plane have a great importance in terms of the general movements of the Anatolian Block along the E-W direction. We conclude that the normal and shear strains appear to be a very subtle barometer for tectonic stress conditions within Turkey, and that strain analysis can be of great importance in understanding the nature and characteristics of seismicity of the country.

IASPEI (Seismology, Geophysics)

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S01bp-318

Crustal tomography of South-Eastern Alps

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The Local Earthquake Tomography (LET) has a fundamental role in the comprehension and the improvement of geological information about the 3-D Earth structure. This is useful also for seismological applications as event locations in 3-D velocity models.

In this work we applied LET study in a wide area (180*60 square kilometers), which includes part of Veneto, Friuli Venezia Giulia and the Western portion of Slovenia. We considered about 180 events occurred from 2004 to 2013 and recorded by the C3RN (Central Eastern European Earthquake and Research) network. The cross-border network allowed for the first time to have a faithful reconstruction of the tectonic setting in an active zone between the Italian and Slovenian borders.

Each event has been manually picked (we consider about 1960 waveforms, 1350 P- and 610 S- phases) and located with a common technique of non-linear inversion NLLOC, which searches for a smaller grid than the initial one.

For the tomographic inversion, we adopt the CAT 3-D software, commonly used only for the exploration geophysics. In this study, we rearrange it and set it in order to solve our seismological problem. In our case, we chose three different velocity models (Costa et al., 1992, Gentile et al., 2000 and Bressan et al., 2012) to verify how the initial conditions affect the final 3-D model.

The final results obtained by the three 3-D initial models showed that they can be related to the available geological sections and other geophysical data. The investigation was thus significant to understand geological structures and seismic events locations in an important tectonic area between Italy and Slovenia.

Therefore, we showed that the CAT 3-D software is a valuable tool to resolve not only seismic investigations, but also seismological issues.

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iLoc: new developments on the ISC locator

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The new location algorithm developed for the International Seismological Centre (ISC) has been operational since January 2011. By providing improved hypocentre and magnitude estimates, the ISC locator has increased the efficiency and productivity of the ISC review process to generate the reviewed ISC bulletin. A new development branch has spun off the ISC locator in 2014, the iLoc locator. iLoc by default supports local and regional travel-time predictions provided by the Regional Seismic Travel Time (RSTT) software package developed by the US DoE National Laboratories. Albeit not fully integrated with SeisComp3, iLoc can communicate with the SeisComp3 database. It also supports the new International Seismic Format (ISF2) as well as the new standards for the International Registry of Seismographic Stations. Further development plans include support for full 3D velocity models, such as LLNL-G3D, as well as for local velocity models. The performance of iLoc is demonstrated by relocating recent, globally distributed events from the PDE bulletin. The iLoc locator can be downloaded from the ORFEUS software depository.

IASPEI (Seismology, Geophysics)

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S01bp-320

Ground classification and seismic geotechnical characteristics in Eastern Ardakan city

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The aim of this study is to classify the ground in Ardakan city, Central Iran, based on microtremor data analysis and soil properties. Combining geotechnical, microtremor, and seismic borehole data in one step shows a fair evaluation of seismic characteristics and site response in east of Ardakan. All the data used in this work were interpreted using one dimensional linear method. On the basis of the results obtained in this site, the amplification coefficient occurred approximately around the frequency of 2-3 Hz .The natural frequency increases from2 Hz to 3.04 Hz in the north east to south east region, where the change is proportional to the shear wave velocity and thickness of alluvium. There are various ground classifications purposed for different parts of the world on basis of site effect analysis. Most of these classifications considered the shear wave velocity and fundamental frequency or period as the basic parameters. Also in Iran, some ground classifications such as those of Building Design against earthquake Code, standard 2800, and Komakpanah et al. in east-central Iran are available. In this paper, ground type of Ardakan city was evaluated using microtremor analysis results (about 30 points) and soil profile properties of 2 boreholes. Compared to the acquired ground classifications of boreholes and their soil profiles properties, uniform ground type was revealed for all boreholes. Moreover, using the geotechnical properties of the boreholes, the ground type in this area were determined by standard2800 classification of Iran.

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S01bp-321

Local earthquake tomography including steep topography at very local spatial scales – Mount Hochstaufen, Germany

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The Mount Hochstaufen in SW Germany is known for earthquake swarm activity within the mountain above sea-level. There is a clear relation between increased rain rates and swarm activity with a delay time of on average eight days. It is assumed that the increase of pore fluid pressure reduces the effective normal stress and thus the strength of predefined faults. However, the physical details behind the phenomenon are not very well understood, especially because not all rain events trigger earthquake swarms.

A detailed 3D structural model is an essential pre-condition for further studies to explore this relation between precipitation and earthquake swarm activity. So far, a simple block model with a homogeneous upper crust down to 6 km and a E-W oriented vertical discontinuity is the best model in use. This model proved to be very successful for earthquake location. However, it is not sufficient for e.g. waveform modelling.

Here, we present results of a local earthquake tomography study based on ray theory using an advanced version of the code simulps. At Mount Hochstaufen tomography studies are hampered due to topographic heights of up to 1800m on a spatial length of less than 10 km. Because the effects of topography can bias tomographic results drastically, the advanced version of the used code is considering the topography, which is not a standard approach yet. In a second step, the findings of the ray tomography will be re-checked and refined by a finite-difference tomography.

Together with the results of the ray tomography, here, we will discuss the difficulties during inversion for tomography due to topography and how they are resolved at Mount Hochstaufen.

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Mantle wedge heterogeneous structure beneath the Japan Sea revealed by long-term seafloor seismic observations

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We conducted the repeating long-term seismic observations using Long-term ocean bottom seismometer(LT-OBS)s in the central Japan Sea from 2001 to 2004 and from 2013 to 2014. We apply travel-time tomography method to the regional earthquake and teleseismic arrival-data recorded by LT-OBSs and land stations. We obtained the P and S wave tomographic images down to a depth of 300 km beneath the Japan Sea. The tomographic P-wave image has a high velocity anomaly in the mantle wedge extending down to a depth of approximately 150 km beneath the Yamato Basin. In addition, the resulting tomographic image has three low-velocity anomalies in the mantle wedge. First, an inclined low velocity anomaly approximately parallel to the Pacific slab within the mantle wedge is observed in the around 100 km upper part of the Pacific slab. Second, low velocity anomalies are imaged at a depth of 150 km beneath northeastern Japan and 250 km beneath central Japan. Third, a low velocity zone is imaged from just above the subducting Pacific slab at a depth of 300 km. These low velocity anomalies are interpreted to be represented melt production affected by the fluid dehydrated from Pacific slab. The depth of dehydration from subducting slab is consistent with the results of numerical modeling studies. Our observations suggest that deep dehydration from the Pacific slab occurs at a depth of approximately 300 km and the Pacific plate subduction drives a large-scale upwelling flow beneath the Japan Sea.

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Temporal changes of seismic velocity in crustal associated with M > 6.0 earthquakes, Taiwan in recent years

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Changes of seismic velocities in the crust can be found after occurrence of earthquakes and volcanic activities. There are several methods to detect these variations. One of general method is finding time lapse between two stations, which can be represented by variability in seismic velocity, by using the empirical Green's function (EGF) retrieved from cross-correlation function of continuous seismic coda waves or ambient noise. However, waveform cross-correlation-based method only reveals the differences surrounding the ray path of pairs. A potential solution to understanding 3D velocity changes before and after a large earthquake is using results of tomographic images. In this study, we use seismic tomographic method with the relocated earthquake catalog and the combination of permanent stations from the Taiwan Central Weather Bureau Seismic Network (CWBSN) and temporal Taiwan Integrated Geodynamics Research (TAIGER) array. We analyzed several cases of earthquakes with magnitude larger than 6.0. Tomographic results are obtained before and after the occurrence of these study events. In comparison the tomographic results, we found the both increasing in V_p and V_p/V_s ratio in vicinity of source area after the occurrence of these study events which might imply the fluid injected into the source rupture zone.

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Receiver function travel time tomography

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Travel time tomography usually assumes the smooth 3D seismic velocity structure, except for the studies by Zhao et al, (1992), who introduced the velocity discontinuities. They fixed, however, them in the iterative processes of inverting 3D velocities in each layer. Hirahara et al. (2006) proposed ‘Receiver Function Tomography (RFT)’, which determines also the velocity discontinuity interfaces and the velocity contrasts across the interfaces by inverting the RF waveforms. Unfortunately, they found RFT is difficult at present.

Instead, we are developing RF Travel Time Tomography (RFTT) using only arrival times from local and teleseismic events and P-Ps times obtained with RF analyses. Abe et al. (2011) developed a method to estimate steeply dipping interfaces of velocity discontinuities from common conversion point stacking of RFs, where the multistage fast-marching method (de Kool et al., 2006) is used to calculate the ray bending.

They studied the Kyushu region, southwest Japan, beneath which the Philippine Sea slab subducts, assuming ak135 velocity model. The 3D cell stacking of vectorial RFs which are rotated for bending rays at the estimated interfaces give the Ps phases, whose P-Ps times can be used. Using RFTT, we extend their study to estimate the 3-D velocity structure together with the velocity discontinuity interfaces such as the continental Moho, the top of the subducting slab, and the oceanic Moho. In the talk, we first describe some details of the data preparation procedure of P-Ps time data, in addition to direct arrivals from local and teleseismic events. At present, we use FMTOMO (Fast Marching Tomography) by Rawlinson (2007) or our extended one in RFTT analyses

IASPEI (Seismology, Geophysics)

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S01bp-325

Joint inversion of seismic and gravity data for velocity structure and hypocentral locations of the Colombian subduction zone

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Joint inversions of geophysical data recover models that simultaneously fit multiple types of constraints while taking advantage of the differing sensitivities of each data type. Here, we combine body wave arrival times with surface wave dispersion measurements and gravity observations to develop a combined 3D P- and S-wave velocity model for the crust and upper mantle of the Colombian subduction zone. P- and S-wave arrival times were obtained for local earthquakes from instruments in the Colombian National Seismic Network. Rayleigh wave dispersion curves were inverted for using a subset of network stations and larger local earthquakes. Gravity observations were extracted from the global satellite-based model EGM2008.

Preliminary results show reduced velocities beneath the volcanic arc in the upper 30 km of the crust. Hypocentral relocations indicate a clear discontinuity in intermediate-depth seismicity centered at 5° N latitude, where the southern region of seismicity is ~200 km trenchward of the northern portion, coincident with the termination of arc volcanism, which has been recently interpreted to be due to a slab tear [Vargas and Mann, 2013]. High velocities associated with the subducting slab(s) also indicate a discontinuity below 100 km depth between the southern (Nazca) and northern (Caribbean) portions of the subduction zone. The northern portion of the subduction zone is generally characterized by broadly elevated velocities, which may be consistent with a slab of an old, thickened Caribbean Plate origin. The interaction between the edges of the Nazca and Caribbean slabs may contribute to the seismicity of the Bucaramanga nest.

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Simultaneous determination of the 1D velocity structure and hypocentral parameters in the Gyeongju area, South Korea

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It is possible in theory to simultaneously determine hypocentral parameters and the velocity structure including boundary depths, provided focal depths of events are uniformly distributed throughout layers. A new algorithm uses the best fitting velocity model which minimizes the differences between observed and computed traveltimes to determine accurate hypocentral parameters. The best fitting velocity model is obtained from the top layer to the bottom layer in regular sequence using iterative (grid searching) method among numerous velocity models. Accuracy tests for this algorithm are carried out using traveltime data synthesized employing an accurate two-point ray tracing technique with the known velocity structure and hypocentral parameters of events. Numerical tests show that the maximum errors in velocities and boundary depths are about 0.06 km/s and 0.15 km for error-free synthetic data, and about 0.12 km/s and 0.17 km for noisy data obtained from error-free synthetic data by adding random noise having 0.1-s standard deviation. We applied the new algorithm to the Gyeongju area earthquake data observed by a 20-station local seismic array network distributed over 40×50 km^2 area. The estimated velocity structure is higher than those obtained by previous independent works, and the boundary depths are not clearly estimated in contrast with the results using synthetic data.

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Seismic array observation and lithospheric structure in the southwestern region of China

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The China Seismic Array Program (ChinArray) is to understand the deep structures and their relationship to seismic activity in the continent of China. The first phase of the program was carried out in the region of Yunnan, in the southwestern of China. The region is located at the southeast margin of Tibetan Plateau. How is the relationship between the Plateau and surroundings blocks? How is the characteristics of the deep structures, especially along the faults? We also want to know more about deep backgrounds of the earthquake occurrence. The seismic array we installed includes 350 broadband portable seismic stations, with the average interval of 35km. By using the seismic inversion methods, we obtained the 3-D seismic velocity structure, the shape of the Moho discontinuities, the seismic anisotropy of the lithospheric medium. These results could be used to build the 3-D model of the lithospheric structures. The low velocity zone was founded inside the Plateau area. Moho depth distribution was obtained from the seismic receiver function. They showed the different margins of the extension materials of Tibetan Plateau in deep from that on the surface. The Red River fault is the border of the blocks in crust. While it has no remarkable variation in mantle beneath the Red River fault. The seismic anisotropy figure showed that the directions of the splitted fast S waves in northern and southern part of the Yunnan area are different. We deduced that this may be related to the eastward subduction of the Indian plate.

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Incorporating normal mode data into the Comprehensive Seismic Earth Model

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We aim to combine long period normal mode modelling with shorter period full waveform inversion within the multi-scale framework of the Comprehensive Seismic Earth Model.

Advances in high performance computing and numerical methods allow the computation of realistic seismic wave propagation through complex media, ensuring that the complete wave field is correctly represented in synthetic seismograms. This full waveform inversion is widely applied on regional and continental scales, taking advantage of particularly dense data sampling and obtaining increased resolution. However, global full waveform models are still and will continue to be limited to longer length scales due to computational costs.

Normal mode tomography is a fast and full waveform approach to constrain seismic structures in a global way, which is essential to obtain a correct long wavelength background model as well as to produce more accurate absolute velocity models for tectonic and mineral physics interpretations. In addition, it is vital to combine all seismic data types across accessible periods to obtain a more complete, consistent and interpretable image of the Earth's interior.

The recent development of the Comprehensive Seismic Earth Model (CSEM) provides a natural multi-scale inversion framework for combining long period normal mode data with full waveform inversion. This allows exploitation of the full waveform capacity on both sides of the seismic spectrum. We report here on the initial steps of this process in which we first develop a mediator between the existing CSEM framework and normal mode calculations, in order to test the current state of the CSEM using normal mode splitting function data. Subsequently, we will work towards CSEM updates that are consistent with normal mode data.

IASPEI (Seismology, Geophysics)

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Empirical travel-time tables for the SIL network in Iceland

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We estimate empirical travel-time (ETT) tables for each station by interpolating the travel-time observations from the South Iceland Lowlands (SIL) database mapped to the hypocentre of each event. We decompose the traveltimes into three additive parts: 1) the prediction of a 1-D reference velocity model; 2) deterministic variation of residuals from that 1-D model constructed by smoothing over a regional scale; and 3) a smaller-scale, stochastic component. We study the distance-dependent covariance of the stochastic component, separating it into a spatially incoherent part (noise) and a spatially coherent part (remaining structural signal). The stochastic structural component is then interpolated to achieve a local fit to within the local error estimate.

The SIL database is based on locations using 5 different 1-D velocity models for different regions. The arrival times were re-referenced to one single model (the SIL model). Minor discrepancies in archived travel-time reduction were identified and removed together with outliers.

Results for P phases indicate a total variance of residuals referenced to the SIL model of 0.018 s^2. 60% of the variance are absorbed by regional variations. The incoherent part of the remaining variance increases smoothly to a distance that roughly corresponds to the P/Pn cross-over and accounts for approximately 20% of the total variance. Picking inconsistency has an average of 0.06 s at short range and the error distribution resembles an exponential distribution.

The resulting ETTs are useful for improved earthquake location, where the error estimation serves as a useful guideline for data weighting. We can construct “cleaned” travel-time residuals from the ETTs to use as input into 3D tomography.

IASPEI (Seismology, Geophysics)

S01bp - S01b Seismological Observation and Interpretation: 3D Velocity Models for Seismic Observatory Applications

S01bp-330

Local earthquake tomography in the Tjornes fracture zone (North Iceland)

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The Tjörnes Fracture Zone (TFZ) is a transform zone connecting the Kolbeinsey Ridge with North Iceland. Most of the zone is offshore, which limits the historical information and geological observations. In order to improve our understanding of the structure of the TFZ, a temporary seismic network was operated offshore on the insular shelf of Iceland and onshore in North Iceland between June and September 2004, as part of the North ICeland Experiment (NICE). Data from this seismic array and data from the permanent Icelandic Network (SIL) have been used to constrain the sub-surface structure using local earthquake tomography. Comparison between results including and without NICE data shows the capability of this denser network to illuminate the upper-most crust. Although the microseismicity registered by the NICE network is dominated by low-magnitude shallow events, SIL data recorded for more than ten years are useful to get information about the deeper crust.

The results from the tomography reveal a transition from anomalously thick Icelandic crust to a more typical oceanic crust to the north of Grímsey. A low-velocity anomaly is observed beneath Flatey Island along the Húsavík-Flatey Fault (HFF) that accommodates the main transform motion of the TFZ. Major velocity anomalies are also found along the Grímsey lineament – one of the two additional seismic lineaments that is parallel to the HFF. The clustering of the refined earthquake locations is enhanced in the 3D velocity models. The seismicity is concentrated along the Grímsey Lineament, the Húsavík-Flatey Fault and a possible transversal lineament between them. Seismicity associated with the Grímsey lineament varies in depth down to 15 km.

IASPEI (Seismology, Geophysics)

S01ca - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-0509

A unique Borehole seismic network to study the continued seismicity in Koyna-Warna region, Western India

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In the Koyna Warna area of Western India, a site well known for its reservoir triggered seismicity, the accuracies of the hypocentral parameters based on the surface broadband seismic network is limited to about 300m. This is mainly due to the presence of a thick heterogenous basalt layer on the top and the inaccessibility of the near-source region for deployment of seismographs. To resolve this problem and to precisely delineate the sub-surface structure, a borehole seismic network of 8 stations is planned, with seismometers to be installed at the bottom of exploratory boreholes at 1 to 1.5 km depth. These boreholes have been drilled under the preparatory phase of a scientific deep drilling program, an initiative taken by the Government of India to study the earthquake mechanism in the Koyna Warna region. Installation of borehole seismometers has been successfully completed in four boreholes drilled to depths of 1522m, 1196m, 1200m and 1503m. Another set of four boreholes will soon be instrumented. This network will be useful to obtain accurate hypocentral locations with a few tens of meters accuracy due to the fact that both the earthquakes and the seismometers are inside the basement where the noise levels are extremely low and arrival times of phases are devoid of errors generated by varied travel times in the overlying basalt. Micro-earthquakes with magnitudes as low as M_L0.3, are clearly recorded at these borehole stations. Preliminary results from the borehole seismographs are presented.

IASPEI (Seismology, Geophysics)

S01ca - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-0510

Seismological investigations related to scientific drilling at Koyna, India

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The Koyna region located close to the west coast of India is an outstanding example of Reservoir Triggered Seismicity (RTS), where triggered earthquakes have been occurring in a restricted area of 20x30 sq km since the impoundment of Shivajisagar Lake in 1962. These include the largest triggered earthquake of M 6.3 on 10 December 1967, 22 earthquakes of M ³ 5.0 and several thousand smaller earthquakes. The continuing seismicity in the Koyna region especially at shallow depths, therefore, forms an excellent site for scientific deep drilling, to enable direct measurement of the physical and mechanical properties of rocks, pore fluid pressure, hydrology, temperature and other parameters of an intra-plate, active, fault zone in the “near-field” of earthquakes – before, during and after their occurrence. Focal depths are estimated using waveform inversion approach and are mostly in a region within 6 km in the Warna region that can be accessed by drilling with the available expertise. Also, well constrained fault plane solutions are derived which provide vital information regarding the orientation of the fault planes. Analysis of the 14 April 2012 earthquake of M_w 4.8 has indicated a $N30^0E$ oriented left-lateral strike-slip fault plane along the Donachiwada fissure zone associated with the largest M 6.3 Koyna earthquake of 1967. Seismicity trends are delineated by relocating the seismicity clusters and aftershock locations. The results from these studies have provided vital inputs on the exact location and depth of the proposed scientific deep drilling program. The borehole network being deployed will further refine these crucial inputs.

IASPEI (Seismology, Geophysics)

S01ca - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-0933

Scientific drilling in Koyna, India to study reservoir triggered earthquakes: heat flow, subsurface temperatures and implications for seismogenesis

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Scientific core drilling at 8 sites up to a depth of 1522 m in Koyna region, western India provided a rare opportunity to characterize the geothermal regime and study its implications on seismogenesis in the top ~10 km of the crust. The boreholes penetrated the Deccan basalt and sampled a few hundred metres of the underlying granitic basement rocks for the first time in the region. Salient results are as follows. (i) Equilibrium temperature measurements carried out to a depth of 1522 m in borehole KBH-1 yield gradients of 26.5 mKm-1 in the basalt and 15.7 mKm-1 in the granitic basement. The contrast is consistent with thermal conductivity contrast between the two rock types, yielding a robust heat flow estimate of 43 mW m-2 for the Koyna region. Measurements in other boreholes are in line with the KBH-1 results. (ii) Heat flow is low, characteristic of Archaean cratons. (iii) Radioelement analysis on 45 basement core samples revealed low Th (1-16 ppm) and U (near-zero to 1.6 ppm), yielding radiogenic heat production in the range 0.4 to 2 μWm^{-3}. (iv) Considering a range in heat flow (40-50 mW m^{-2}) and a range in heat production (0.5-1.5 μWm^{-3}) of the basement rocks, upper and lower bounds of temperatures computed at a depth of 6 km range between 130 and 150 ^{o}C. (v) This study supports brittle rupture in the “cold” upper part of the crust, and a strong candidate for failure in this regime could perhaps be anomalous pore fluid pressures at seismogenic depths. (vi) The study provides important constraints for the design of the proposed fault zone observatory in Koyna region.

IASPEI (Seismology, Geophysics)

S01ca - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-1720

Investigation of Reservoir Triggered Earthquakes through Deep Scientific Drilling at Koyna, India

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Triggered earthquakes are occurring since impoundment of the Koyna Dam in 1962, near west coast of India, including M 6.3 December 10, 1967; 22 M>5, and thousands of smaller earthquakes. The entire earthquake activity is limited to an area of about 20 km x 30 km, with most focal depths being within 6 km. There is no other earthquakes source within 50 km of the Koyna Dam. An ICDP Workshop held in March 2011 found Koyna to be the most suitable site to investigate RTS through deep drilling. Studies carried out in the preparatory phase since 2011 were reviewed in the second ICDP Workshop held at Koyna in 2014. Results of detailed airborne magnetic and gravity-gradient surveys, MT surveys, drilling of 6 boreholes going to depths of ~ 1500 m and logging, heat flow measurements, seismological investigations including the deployment of two borehole seismometers, and LiDAR surveys were reviewed. Significant results include absence of sediments below the basalt cover, the thickness of the basalt column and its relation with the surface elevation, and almost flat topography of the basement. The temperatures at the depth of 5 km would be around 130 to 150 degrees Celsius. Seismometers need to be placed below the basalt cover to improve hypocenter locations. Out of 8 planned borehole seismometers 4 are already in operation. A proposal, meeting the 15 January 2015 deadline, has been submitted to ICDP for technical help in drilling two pilot boreholes. The future plan of work includes:

• Drilling 2 pilot boreholes of 3 km depth during 2015.

• Concurrent planning of deep borehole(s), firming the specifications by the end of 2015 and drilling and setting of deep borehole observatory during 2016 and 2017.

• Plan for an international meeting and visit to Koyna in 2017.

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S01ca - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-1955

Alteration in cyclicity of reservoir induced seismicity in Koyna-Warna area in relation with relative strong earthquakes

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The comparative analysis was carried out for the dynamics of reservoir induced seismicity (RIS) in the seismic area Koyna-Warna (Western India) and annual variations of the water level in reservoirs in period of 1961-2013. The cyclic variations of water level cause the cyclic response of seismicity in two zones of seismic area between Koyna and Warna reservoirs. The cyclic response of seismicity was found to be disappearing after doublet of earthquakes with M>5 in 2000. Then, the cyclic response of seismicity appears after 2006 again. Similar effect was found previously in laboratory experiment for acoustic emission response to the periodic variations of the axial loading.

IASPEI (Seismology, Geophysics)

S01cb - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-1959

Analyses of surface structural trends at Koyna-Warna region,Deccan Volcanic Province Western India with reference to trends of subsurface active faults

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The Koyna-Warna region in western India is a well known site of reservoir triggered seismicity (RTS), where the world's largest triggered earthquake of M6.3 was recorded in 1967. Since then seismicity has been continuously recorded in the area, presumably triggered by the Koyna and the Warna reservoirs in the north and south respectively. The active faults inferred to be at depths of 5-15 km, generally have a strike-slip or normal faulting mechanism as inferred from seismological studies. Due the pile of Deccan lavas, Surface observations of the active faults in the basement are sparse, mostly confined to lineaments inferred from regional satellite imagery. In the present study, a focused attempt has been made to trace the surface lineaments and fracture alignments from satellite images and outcrop measurements in the Koyna-Warna region. Predominantly NE-SW or NW-SE oriented faults and fractures are obtained, which correlate well with the subsurface faults, implying that the causative stress field, generally attributed to the India-Eurasia plate collision, is common for both the seismogenic granite basement and the overlying Deccan basalts. Instances of folded or deformed features in unconsolidated sediments along river banks and within fan shaped ridge bases have provided fresh insights to the study. Further, based on surface observations and subsurface geophysical interpretations, we evolve a model of conjugate fault systems to explain the neo-tectonics of the Koyna-Warna region.

IASPEI (Seismology, Geophysics)

S01cb - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-3832

Examples of induced/triggered seismicity in Italy: State of the art and perspectives

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The relationship between anthropic operations and seismic events has increasingly drawn the attention of the international scientific community during the last decades. Especially in Italy and after the Emilia seismic sequence of May 2012, this topic sparked a new particular interest. Several round tables and ad-hoc commissions were set up in order to define the state-of-the-art of induced/triggered seismicity (ITS), in association with the publication of guidelines for its discrimination and monitoring. According to this, the following human activities have been defined as relevant for the generation of ITS: reservoir impoundments, geothermal production, hydrocarbons exploitation and mining. Unfortunately a review of historical ITS-related earthquakes seems to be a difficult task due to the poor data quality from historical records. Despite this, some promising results were obtained by a re-evaluation of several hypothesized historical ITS-related events. Considering the high seismicity of the Italian peninsula, the evaluation of actual ITS requires new discrimination approaches and high resolution seismic monitoring facilities for a reliable distinction between anthropogenic and natural seismicity. In this context a close cooperation with the industrial companies for accessing the production data would be desirable, if not necessary. This contribution presents an overview of the recent researches performed in the framework of INGV-projects and other ongoing activities.

IASPEI (Seismology, Geophysics)

S01cb - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-4059

A constrained 3D density model of the upper crust beneath koyna-warna seismicity region, western India

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Koyna-Warna region, western India is the site of the largest artificial water reservoir triggered earthquake of M 6.3 on 10th December, 1967. Triggered earthquakes began soon after impounding the Koyna reservoir in 1962 and have been continuing since then. As part of the multi-parametric geophysical and seismological investigations, 5000 line km of Airborne Gravity Gradiometer and high-sensitivity Magnetic data (AGGM) are recorded over the region with flight line spacing of about one km to decipher subsurface structure. Gravity Gradient maps show two distinct trends: N-S trend prominent in the north of Warna reservoir; and a NW-SE trend, south of Warna reservoir that cuts across the Western Ghats.

A 3D inverse modelling of AGGM data allowed inferring subsurface density structure of the region to a depth of 12 km. The thickness of Deccan basalts, which cover the study area, is mainly estimated from the modelling of the magnetic data supplemented with information from several boreholes drilled through basalts. Model suggests an anomalous N-S oriented high density zone bound by low density rocks on either side in the north of Warna reservoir. Other prominent features are NW-SE oriented high and low density zones, south of Warna reservoir. The densities of sub-basalt rocks vary from 2650 to 2800 kg/m^3. Interestingly, the majority of earthquakes are located at the contacts between rocks of contrasting densities.

IASPEI (Seismology, Geophysics)

S01cb - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-4241

Induced seismicity during reinjection of waste water in a geothermal field at Hengill, southwest Iceland

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A large number of microseismic swarms were induced during the reinjection of geothermal fluid at the Hellisheidi geothermal power plant near Hengill volcano in southwest Iceland. The area is tectonically active, located at the triple junction of an oblique spreading zone (Reykjanes Peninsula), a rift zone (the Western Volcanic Zone) and a transform (the South Iceland Seismic Zone). It is characterized by N30°E striking normal faults and N-S striking right lateral strike slip faults. The injection started in September 2011 and the seismicity increased shortly after, with thousands of events recorded by the Icelandic Meteorological Office. The majority of events were small (M_l < 3.0), but the two largest events reached M_l 3.8 and were widely felt in the area. An increase in seismicity was also observed during the drilling of the injection wells, associated with the loss of drilling fluid. All these events were recorded by a dense network of seismographs operated in the area by Uppsala University, MIT, Reykjavik University, the Icelandic Meteorological Office (IMO), and Iceland Geosurvey from 2009 to 2013. The waveforms of events located by the IMO network were grouped into families based on waveform similarity. By using a typical event from each family as a template for cross correlation of the continuous dataset we were able to find more events than had previously been achieved. Cross correlation differential travel time measurements were then used to relocate the expanded dataset of events. The location and occurrence of earthquakes are then associated with the injection processes. The authors would like to acknowledge the IMO for access to waveform data.

IASPEI (Seismology, Geophysics)

S01cc - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-1532

Can we consider the 1951 Caviaga (Northern Italy) earthquakes as non-induced events?

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Two moderate earthquakes occurred in Norther Italy on May 15th and 16th, 1951, close to the small town of Caviaga.
Coeval studies suggested to relate their origin to oil and gas withdrawal going on in the area.
In the present study we revise the location of these earthquakes and discuss the reliability of their possible dependency on human activity, applying modern location methods and collecting data on historical seismicity and regional tectonics.
From the tectonic point of view this part of the Po Plain is certainly active, although with low deformation rate, controlled by the convergence of the Southern Alps and the Apennines active fronts. In the region, previously defined aseismic, at least one historical event occurred in 1786, with a distribution of effects similar to the one observed for the 1951 earthquakes; macroseismic data for both cases are expressly revised here and show the characteristics of deep events.
New locations of both seismic events, computed with two different codes to maximise the use of seismological available data, show that the hypocentral depths are deeper than previously defined, in a range between 13 and 35 km; furthermore epicentres move away northwards from the Caviaga oil and gas fields. All our findings point to the evidence that these events occurred at greater depth with respect to typical values for induced seismicity.
In the light of the results of this work we conclude that the two earthquakes show the features of tectonic events.

IASPEI (Seismology, Geophysics)

S01cc - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-1782

Violations of Gutenberg-Richter relation in anthropogenic seismicity and their consequences for seismic hazard assessment

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Anthropogenic seismicity (AS) environments are shallow hence their heterogeneities have important impact on AS. Moreover, AS is controlled by complex and changeable technological factors. This complicated origin of AS explains why models used in tectonic seismicity may be not suitable for AS. We study here five cases of AS, testing statistically whether the magnitudes follow the Gutenberg-Richter relation or not. The cases differ in inducing technologies, in the duration of periods in which they were recorded, and in the ranges of magnitudes. In all five cases the observed frequency-magnitude distributions significantly differ from the Gutenberg-Richter relation. It appears that the incoherence of the observed frequency-magnitude distribution with the Gutenberg-Richter relation may be a dominant feature of AS, regardless of the technology inducing earthquakes. In these circumstances, in order to properly estimate magnitude CDF for seismic hazard analysis purposes in AS, a model-free approach based on kernel non-parametric estimators is proposed. This estimation method performs well for any kind of background distribution, in particular for larger values of actual CDF, the instances the most important for hazard analysis. Hazard functions can be provided together with confidence intervals assessed by means of resampling (presentation by Orlecka-Sikora B. this session). We also show on the studied samples that the use of the exponential model to non-exponentially distributed data can imply severe errors of hazard parameters.

This work was done in the framework of IS-EPOS: Digital Research Space of Induced Seismicity for EPOS Purposes project, funded by the National Centre for Research and Development in the Operational Program Innovative Economy in the

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IASPEI (Seismology, Geophysics)

S01cc - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-3700

Discriminating seismic sources (mining-induced seismicity, fluid injection induced seismicity, and tectonic earthquakes) in central Utah, USA

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An important goal of induced seismicity studies is to clearly discriminate induced earthquakes from naturally occurring earthquakes. In this study, we analyze seismic events recorded in central Utah along the Wasatch Plateau and Book Cliffs. This region has at least two, and potentially three, distinct seismic events types: (1) mining-induced seismicity (MIS) associated with underground coal mines; (2) tectonic earthquakes that are part of the intermountain seismic belt (ISB), a continuous band of seismicity that extends from Montana to Arizona; and (3) potentially induced seismic events associated with waste water injection wells. While MIS and earthquakes have been documented in this region, fluid injection events have not. There are, however, several injection wells in the region and it is important to determine if the injection is contributing to the seismicity. To discriminate among event types in this region, we use the University of Utah Seismograph Station catalog of 23,573 seismic events ($-0.84 < M < 4.2$) recorded from 1981 to 2014. Using waveform matching techniques and a single-link clustering algorithm all events are grouped by waveform similarity. MIS in this area typically tracks with production, so we use mine permit boundaries and production history to identify MIS clusters. Seismicity that does not track with mine history is compared to the location of fluid injection sites. Subspace detectors are run to lower the magnitude threshold for these clusters, and the events are relocated using relative location techniques to determine if the seismicity migrates along diffusion-like curves in time and space. Events that are not clearly associated with either MIS or fluid injection are placed in the tectonic earthquake category.

IASPEI (Seismology, Geophysics)

S01cc - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-3797

A study on the criteria for discerning natural from induced seismicity: The larderello-travale geothermal Field (Italy).

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Located in central Tuscany, Italy, the Larderello-Travale Geothermal field (LTGF) is the oldest geothermal power plant of the world, and it presently produces about 10% of the world's entire supply of geothermal electricity. The area is seismically active; the maximum intensity (VII-VIII Mercalli scale) was recorded in 1724, well before the establishment of the first geothermal power plant. Recent seismicity is characterized by low-magnitude (<4) events, whose rates (but not magnitudes) were found to correlate positively with injection rates. A primary need thus consits in discerning whether that seismicity is related to the energy production cycle, rather than to a 'natural' background activity at the site. We addressed this issue by conducting a seismological survey using a dense deployment of up to 20 broad-band instruments. During the May 2012-October 2013 time interval, we located about 2000 earthquakes, mostly concentrated around the deep geothermal production wells at depths shallower than 10 km. Notwithstanding the lack of information on extraction and injection rates, hints for induced seismicity are found in the occurrence of numerous seismicity bursts each accounting for hundreds of earthquakes tightly clustered in space (few hundreds of meters) and time (generally a few hours). Exploiting waveform similarity within individual clusters, we derived accurate catalogs which were analysed in terms of (i) magnitudes and inter-event times distributions, (ii) temporal evolution of energy release, and (iii) moment / fault-area relationships. On the base of these characteristics, individual earthquake groups exhibit different behaviours that likely represent the manifestation of distinct mechanisms triggering fault failure.

IASPEI (Seismology, Geophysics)

S01cc - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-4089

Discrimination between induced and natural seismic activities.

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Ten samples of seismic activities in the regions of oil production, mining, geothermal power plants, strong explosions, electromagnetic and seismic explorations were considered. Comparison of induced and natural seismicity data sets allowed to suggest the following discriminating features of them: 1) b-value of magnitude-frequency relationship (the value is higher in case of induced seismicity than in case of natural earthquakes); 2) distribution of time intervals between seismic events (Weibull distribution, in case of the induced seismicity form factor is less than 1); 3) migration of the earthquake hypocenters to/from man activity zone, variation of the seismic event grouping parameters; 4) the presence of deterministic component in the induced seismic activity variations, diminishing of correlation dimension; 5) correlation between seismic activity variation and variations of man action characteristics (injection pressure, injection and/or production volumes and so on); 6) change of the seismic mechanisms of induced earthquakes in comparison with the natural earthquakes.

Change of the above parameters in the regions of industrial activities can be considered as an indication of seismicity induced by that activity. It should be noted that the effect of man action on the seismic activity change can be not only negative (seismic activity increase) but it can be positive (seismic activity decrease) or neutral (seismic activity parameters change but mean value of seismicity remains the same).

IASPEI (Seismology, Geophysics)

S01cd - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-0966

Stress field estimation from earthquakes focal mechanisms and back projection images.

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One of biggest concern in Colombia is seismicity induced by Oil and Gas operations take place in the Eastern Foreland basin of the country. Over the last years earthquakes with magnitudes ranging up to 4.0 on Richter´s scale have been recorded in areas where seismic activity was considered inexistent. Our hypothesis suggests that water injection is the main cause of this anomalous seismic increased.

The objective of this work is to provide reasonable information about hypocentral solutions and focal mechanisms, in order to understand temporal variation of focal mechanisms and stress drop vs source radius related to seismic activity in the oil field. Records are provided by the National Seismological Network of Colombia. The analysis clarifies some ideas about peaks of seismic energy radiation, fracture length, fracture velocity, fracture orientation and fault plane solutions.

IASPEI (Seismology, Geophysics)

S01cd - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-2083

Evolution of pore fluid pressures in the Basel EGS inferred from earthquake focal mechanisms

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We developed an inversion method to estimate the evolution of pore fluid pressure fields from earthquake focal mechanism solutions. The basic assumption in this approach is that seismic slip occurs in the direction of the resolved shear traction acting on pre-existing faults, controlled by the Coulomb failure criterion with a constant friction coefficient. Application of the method to induced seismicity in the Basel enhanced geothermal system (EGS) in Switzerland shows the evolution of pore fluid pressure in response to fluid injection experiments. For a few days following the initiation of the fluid injection, overpressurized fluids were concentrated around the injection well and then anisotropically propagated within the reservoir until the well was shut in and bled off. At four representative locations the pore fluid pressure increased together with the wellhead pressure for the first 3–5 days, and reached a ceiling by the time of shutting in. The peak pressure in the reservoir was less than the minimum principal stress at each depth, indicating that hydraulic fracturing did not occur during the stimulation. This suggests that seismic events may play an important role in promoting the development of permeable channels, particularly southeast of the borehole where the largest seismic event (M_w 2.95) occurred. The induced events were primarily controlled by a decrease in fault strength due to an increase in pore fluid pressures. However, the largest event (the mainshock) was not directly related to a drastic decrease in fault strength at the hypocenter. Substantial stress loading by preshocks in a weak zone formed by fluid incursion seemd to promote the dynamic rupture of the mainshock.

IASPEI (Seismology, Geophysics)

S01cd - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-2329

"Rupture process of the March 19, 2013, Rudna Mine (Poland) induced seismic event in view of moment tensor inversion"

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Induced seismic events are usually recorded on local stations provided by mining companies or local authorities. In case of March 19th, 2013 seismic event we have unique opportunity to analyze recorded signals from local in-mine, local surface and regional seismic networks. The availability of three complementary monitoring networks gave an optimal set up to determine the earthquake source parameters and compare the performance and results using data from different installations. We perform waveform and spectral based analysis to infer source properties, with a particular interest to the determination of the rupture processes, using different moment tensor inversion techniques. We used the waveform similarities analysis to validate the results of obtained moment tensors. The moment tensor inversion results are surprisingly different, ranging from a dominant thrust mechanism, resolved at closest distances, to a collapse-type rupture, resolved at regional distances. We proof that a complex rupture model can explain all observations and justify these discrepancies. The final scenario indicates that the rupture nucleated as a weaker thrust mechanism, along a pre-existing weakened surface, and continued in a more energetic collapse event. We propose here a new moment tensor decomposition and an alternative moment tensor fitting procedure, which can be used to analyze the moment tensor of collapse sources. This decomposition allows more fully solve the complexity of such type of events in terms of the moment tensor.

IASPEI (Seismology, Geophysics)

S01cd - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-2410

"Moment tensor inversion of microearthquakes induced by the Háje natural gas storage, Czech Republic"

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Induced seismicity around the Háje natural gas storage area (Czech Republic) is monitored by the Príbram seismological network. Determination of the source mechanisms of microearthquakes generated during operations in gas storage are important for understanding the processes inside because they can indicate the type of fracturing of the rock massif. This knowledge helps to assess the hazard associated to the operation. Sources of four largest microearthquakes, with magnitudes M_w ranging between 0.2 and 0.4, were investigated. All these events were located inside the storage area and at depths similar to those of the underground caverns where the gas is stored. The moment tensor description has been applied in order to assess the source process and recognize whether a significant isotropic component existed that could be interpreted as a possible cavern collapse. Reliability of the retrieval of individual components within the source – shear vs. non-shear – is assessed by evaluating the mechanism by using the alternative source model to the moment tensor, namely the shear-tensile crack, which offers a more robust retrieval thanks to using less parameters to describe the source. Additional check is application of alternative velocity models during the inversion, as failure in modeling the structure may bias the DC vs. non-DC resolution essentially. Thus, apart from the primary homogeneous halfspace approaching well the intact granite massif in the locality, also a simple gradient velocity model is considered. Two from these induced events have been already studied and their source mechanisms have been determined by inversion technique using the software ISOLA for moment tensor retrieval. Our solutions are compared with these results.

IASPEI (Seismology, Geophysics)

S01cd - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-4025

Source parameters of induced earthquakes using regional earth models: Application to the 2013 sequence off the northeast coast of Spain

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We have obtained source parameters (focal depth, moment magnitude and moment tensors) for the 8 largest earthquakes of the 2013 seismic sequence occurred near an underground gas storage off the NE coast of Spain. To determine the regional centroid moment tensors we have used two methodologies: one based on the inversion of complete waveforms and another based on the inversion of spectral amplitudes of Love and Rayleigh waves. Both methodologies give compatible results in terms of focal mechanisms and focal depths, although the method based on waveform inversion provides more consistent results, with almost identical mechanisms and focal depths for all the events in the sequence. The mechanisms of the largest events are predominantly strike-slip (75%) with a smaller normal component (25%). The orientation of the P axes is approximately N-S, consistent with the known current state of stress in the region. The optimum focal depth obtained for all the analyzed events is 8 km, significantly deeper than the depth of injection (approximately 2 km below sea level). To elucidate the cause of this discrepancy we have investigated the influence of the earth model in the results of the source inversion. Therefore we have obtained new shear wave velocity models for the region (both 1D and 3D) based on surface wave dispersion measurements from ambient noise and from the earthquakes of the sequence. Using the 1D model we have determined new centroid moment tensor solutions. These new estimates do not differ significantly from those obtained initially using an earth model representative of the western US, indicating that the depth difference is not caused by the earth model.

IASPEI (Seismology, Geophysics)

S01cd - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-4331

Using posterior entropy for improving accuracy of location error estimation

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The spatial location of sources of seismic waves is one of the first tasks when transient waves from natural (uncontrolled) sources are analyzed. Source activity and its spatial variability in time, the geometry of recording network, the complexity and heterogeneity of wave velocity distribution are all factors influencing the performance of location algorithms and accuracy of the achieved results. While estimating of the earthquake foci location is relatively simple a quantitative estimation of the location accuracy is really a challenging task even if the probabilistic inverse method is used because it requires knowledge of statistics of observational, modeling, and a priori uncertainties. At the same time a reliable estimation of location errors is significant for further uncertainty analysis of such more quantities like events clustering, moment tensor, coulomb stress transfer, dynamic stress drop, to name a few. In this contribution we addressed this task when statistics of observational and/or modeling errors are unknown. This common situation requires introduction of a priori constraints on the likelihood (misfit) function which significantly influence the estimated errors. Based on the results of an analysis of 120 seismic events from the Rudna (Poland) copper mine operating in southwestern Poland we propose an approach based on an analysis of Shanon's entropy calculated for the a posteriori distribution. We show that this meta-characteristic of the a posteriori distribution carries out some information on uncertainties of the solution found and thus can help a more realistic estimation of location uncertainties.

IASPEI (Seismology, Geophysics)

S01ce - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-1909

"EPOS THEMATIC CORE SERVICE ANTHROPOGENIC HAZARDS – TO FACILITATE THE WAY OF ATTAINING EXCELLENCE"

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The community focused on seismic/aseismic deformation processes induced by human operation, organized within European Plate Observing System (EPOS) as WG10 “Infrastructure for Georesources” integrates distributed research infrastructures (RI) to facilitate and stimulate research on anthropogenic hazards especially those associated with the exploration and exploitation of geo-resources, within **EPOS Thematic Core Service ANTHROPOGENIC HAZARDS (TCS AH)**. The innovative element is the uniqueness of the integrated RI which comprises two main deliverables:

(1) Exceptional datasets, called “episodes”, which comprehensively describe a geophysical process induced or triggered by human technological activity, posing hazards for infrastructure, people and the environment;

(2) Problem-oriented, bespoke services uniquely designed for analyzing correlations between technological activities, geophysical response and associated hazards, including e-research environment of IS-EPOS platform (is-epos.eu).

These objectives will be achieved through the Science-Industry Synergy, ensuring bi-directional information exchange, including unique and previously unavailable data furnished by industrial partners and innovative solutions coming back to industry. The data and services are related to a wide spectrum of inducing technologies, with seismic/aseismic deformation and production history dataset.

Impact of RI will be also reflected in a more multidisciplinary approach to education, and an opportunity for students to obtain skills and knowledge in the anthropogenic hazards field.

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IASPEI (Seismology, Geophysics)

S01ce - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-2384

Micro-earthquake detection and seismic hazard estimation for hydraulic stimulations using SeisComP3

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In order to mitigate the risk associated with seismicity caused by hydraulic stimulations in deep geothermal systems so called traffic light systems are used. These systems consist of a seismic monitoring, a method to estimate seismic hazard, and predefined threshold values. We detect micro-earthquakes using a cross-correlation of real time data with seismograms of known master earthquakes. To achieve similarity with events at slightly different locations we use the envelope of the seismic traces. We tested the automatic detections against a manually evaluated earthquake catalogue of the Landau/Insheim geothermal field. The magnitude of completeness of the automatically generated catalogue is Mc= 0.2 using our current parameters, where we do not have any wrong detections caused by noise after one year of automatic analysis. We configured the detector to separate three different classes of events assigned to the Landau and Insheim reservoirs (5 km distance) as well as to Waldhambach quarry (10 km distance). Additionally, we developed a real time method to compute the probability of exceedance for an undesired magnitude using a statistical analysis of recorded micro-seismicity. We compute the magnitude of completeness, the b-value of the Gutenberg-Richter law, and the so-called seismogenic index. These quantities are updated in real time, if more induced earthquakes are detected. This algorithm as well as the detector are integrated in the real-time earthquake monitoring software SeisComP3. The traffic light system is tested using data of the Basel project simulating a real time scenario in play-back mode.

IASPEI (Seismology, Geophysics)

S01ce - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-2524

Analysis of sources and possible effects of anthropogenic seismicity in Argentina, Colombia and Mexico

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A new, international, inter-institutional, interdisciplinary, initiative is being developed in order to study the seismic activity manifestations in the vicinity of several hydrocarbon projects (conventional and no-conventional) in several Latin-American countries.

ASAP - Analysis of **S**eismicity induced by **A**nthropogenic **P**rocesses in Latin-America and Caribbean is a new project, which main goal is the analysis of the potential relationship between earthquakes and hydrocarbon exploitation processes, in order to get a better understanding of how these processes may affect the earthquake background, trigger seismicity and change the tectonic behavior in the Latin-American region.

The principal locations of study are: Outcrops of the Vaca Muerta shales (Argentina), Outcrops of the Middle Magdalena Valley Shales (Colombia), and Outcrops of geothermal fields (Mexico).

The aspects, which make this study relevant, not only for three mentioned countries, but, in general, for Latin-America and Caribbean region, are:

1) New records of unexpected seismic activity, which was not registered before.

2) New initiatives for exploration and production of non-conventional hydrocarbons, which are implemented in this region.

3) Close location of these kinds of exploration and production processes to urban and semi-urban centers.

4) Concern of people about the influence of this sort of processes in the lack of stabilization of sites where these processes are carried out.

5) Concern of communities about the effect of these kinds of processes on the local belongings and traditions.

6) These sorts of exploration and production processes are carried out in the whole Latin-American and Caribbean region.

ASAP Project invites other Latin-American interested institutions to join this initiative.

IASPEI (Seismology, Geophysics)

S01ce - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-2670

Interval estimation of seismic hazard parameters

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The interval estimation of seismic hazard parameters is presented. The solution takes into account an aggregated uncertainty in the activity rate and magnitude cumulative distribution function (CDF). In case of Poisson earthquake occurrence t-distribution is used to model the sampling distribution of mean frequencies. In case of CDF estimation two approaches are considered: parametric and nonparametric. When a Gutenberg-Richter based parametric model of magnitude distribution is used the interval estimation of its parameters is usually based on the asymptotic normality of the maximum likelihood estimators. When nonparametric kernel estimation of magnitude distribution is used, we propose the iterated bias corrected and accelerated method (IBCa method) for interval estimation. This procedure is based on the smoothed bootstrap and second-order bootstrap samples. The number of bootstrap samples is calculated to achieve a desired level of accuracy of the quantile level. The confidence intervals of hazard functions are evaluated from the activity rate and magnitude CDF uncertainties on the plug-in curve of exceedance probability, return period etc. The algorithm performance is illustrated through the analysis of Monte Carlo simulated seismic event catalogues and actual data induced by mining activity and water impoundment.

IASPEI (Seismology, Geophysics)

S01ce - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

IUGG-3583

Application of rate and state models to different types of induced seismicity

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Induced seismicity (IS) is observed for different types of anthropogenic operations including excavation and solution mining, reservoir ponding, conventional hydrocarbon exploitation, reservoir stimulation and hydrofracturing, waste water injection and water pumping. The understanding and prediction of the pattern, rate and frequency-magnitude distribution of IS is a primary goal of probabilistic microseismic studies. Models developed for the specific types of operations are often purely statistical or they combine a predicted pressure and stress change with a threshold-based deterministic trigger model. A unique seismicity model covering the different types of operations is not established.

We combine a standard rate and state seismicity model (RSSM) with hydromechanical and poro-elastic simulations of hydrofractures and pore pressure diffusion. The RSSM accounts for the first order effects of earthquake–earthquake interaction as typically observed during aftershock sequences. RSSM is fast and efficient for spatial-temporal IS simulations. It is able to consider complex loading scenarios representative for different cases of induced and natural seismicity.

We demonstrate implementations for different IS types from mining, hydrofracturing and injection/pumping cycles. The probabilistic description considers uncertainties and is formulated as optimization problem without parametrizing a front or backfront of seismicity. We compare best fitting RSSM parameter for different applications. Stress shadow effects can be explained. Because RSSM is physics-based and well established in seismology, we suggest to use RSSM as standard also of IS studies.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-464

Reservoir triggering seismicity in Greece: An evidence based review

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First filling and water fluctuation in artificial lakes and reservoirs are known causes of local seismicity. In Greece, 117 dams were built over the past 60 years, of which, however, only 22 have a capacity greater than $20x20^6cm^3$ and could thus affect seismicity in a meaningful way. Most of these larger dams have been constructed and operated by the Greek Public Power Corporation (PPC). The paper aims at a comprehensive review of all relevant studies, undertaken so far, and critically examines the evidence of reservoir triggering seismicity and possible accelerated earthquake occurrence provided. The main reservoirs examined include the Marathon, Kremasta, Pournari, Ilarion and Polyphyto artificial lakes, all of which have recorded seismic events associated with their filling and/or operation for the time period up to 2010. Seismic activity that correlates with maximum or minimum water level fluctuations leads to conclusions about a possible triggering seismicity due to a pore pressure diffusion (drained or un-drained response). In each case we review the cross-correlation coefficients between the reservoir levels and triggered events, and discuss the reasons for their association from an engineering geological (mechanical properties of rocks and formations) and seismological (triggered events) perspective. Our work suggests that, whilst in these cases PCC performs very well the task of hydrological and energy management of the reservoirs, it is crucially important to monitor and validate the daily seismicity at and around the artificial lakes for a better understanding of the upmost limit of triggered seismicity, and possible triggered landslides in the areas surrounding its main reservoirs.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-465

Physics of triggered and induced seismisityabstract

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No so long we proposed new theory generation of tectonic earthquakes {Rasulov D.H. and Rasulova, G.D. The Physics of tectonic earthquakes: Tashkent, Fan, 2009, 224 p. (in Russian)}. According theory, before the earthquake the state of rocks in the source are changed from solid into liquid that leads the action of tectonic tension in it to all possible directions. It is shown that liquid source may fulfill the role of natural hydraulic press and by this increases many times the tectonic force acting on the rocks surrounding it. Thus for generation earthquake is necessary availability as tectonic tensions as liquid source. At various technological processes that perturb the boundary conditions in the affected rockmass the state part of it may to change from solid into liquid. At availability tectonic tensions in these places may to observe induced seismicity.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-467

Reservoir induced seismicity in the region of Song Tranh 2 dam, Central Vietnam

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The Song Tranh 2 (STH2) dam is an example of reservoir induced seismicity, with earthquakes of magnitude up to 4.7. The STH2 hydropower construction is located in the Quang Nam province in Central Vietnam. The natural seismic activity of the STH2 region is very low. In the period from 1775 to 1992 only 13 events have been found. First associated with filling the reservoir earthquakes were recorded by seismic stations located away from the reservoir. In order to facilitate seismic monitoring of the STH2 area a seismic network has been built in cooperation between the Institute of Geophysics, Vietnam Academy of Sciences and Technology and the Institute of Geophysics, Polish Academy of Sciences. The network, operating since August 2013, consists of 10 seismic stations, which is sufficient for advanced data processing. Here the first results of monitoring are presented: examples of earthquake focal mechanisms, completeness of catalogs and correlation between water level and the seismic activity. Full moment tensor of the significant events were calculated with amplitude inversion of the first P-wave pulses. Obtained mechanism solutions allow for the first insight of the rupture process triggered by the reservoir exploitation.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-468

Physical Simulation of Earthquake Triggering by Fluid Migration into the Fault Area

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Field experiments and lab studies carried out over the past fifteen years clearly showed the triggering of weak regional seismicity by electrical pulses of 0.6 to 2.5 kA injected into 4 km-length emitting grounded dipole. Physical mechanism of electric earthquake triggering is not clear yet. For the field experiment conditions generated electrical current on 5-10 km depth of earthquake epicenters typical for the studied region (Northern Tien Shan) is 10-7 to 10-8 A/m2 that is too low for earthquake triggering by induction of additional stresses in the rocks. In this case it is reasonable to consider a secondary triggering mechanism based on fluid interaction with an electric current in geomagnetic field resulted in stimulation of fluid migration. The fluid migrated into a seismogenic fault under critical stress state can provide a reduction of its strength due to friction reduction and Rebinder effect resulted in earthquake triggering. For verification of this hypothesis laboratory experiments were carried out on the spring-block model with water injection into the contact area between movable and fixed blocks. The experimental results confirm a possibility of application of fluid mechanism to explain the phenomenon of weak electrical impacts on the regional seismicity. It was shown that at the stress level in the fault area of 0.99 critical value when the lab earthquake (slip of movable block) occurs, the threshold value of fluid action is about of 1% of contact area/volume. For triggering the slip of the spring-block model it is sufficient to inject 0.2–0.3 g of water into contact area that is 0.5% of weight of granulated material (fault gauge) filled the contact area. Application of obtained experimental results for field conditions is discussed.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-469

Wastewater injection, induced seismicity and pore-pressure related variation of crustal properties: the Val d'Agri (Italy) case study.

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The Val d’Agri in the southern Apennines of Italy is an active extensional basin hosting the largest European onshore oil field. The present contribution aims to analyze micro-earthquakes occurred in the period 2006-2014 close to the injection well and in the nearby area in order to evaluate the spatio-temporal evolution of the seismicity and its correlation with the wastewater injection operation. Moreover we intend to investigate variation of crustal behavior expected to be related to pore pressure variation.
Soon after the initiation of the wastewater injection in 2 June 2006 a low magnitude swarm of 111 induced earthquakes was detected by a dense temporary INGV network.
High-precision locations and focal solution of the seismicity point out a portion of a fault closely located to the well bottom, within the water saturated carbonates of the reservoir. Seismicity rate strictly correlates to injection curves and temporal variations of elastic and anisotropic parameters of the crustal volume surrounding the well were observed.
In the period 2006-2014, 219 events were recognized and located using the permanent stations of ENI and of the Italian National Seismic Network, showing that events cluster along a pre-existing NW-SE-trending, NE-dipping fault zone. At the beginning of 2014 the disposal activity experienced a stop and a restart of the wastewater injection. Here we present the preliminary results of the seismic data acquired by a temporary network installed close to the injection well.
Our results indicate that the continuous monitoring of seismicity with high standard networks and procedures is effective to recognize the seismicity diffusion on active and preexisting faults that might be re-mobilized by pore pressure changes related to wastewater injection wells.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-470

"Seismicity and stress field in the vicinity of natural gas fields in NorthernGermany"

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The Northern German basin is a tectonic region of relatively low seismic activity with only singular and weak tectonic events. However, during the last decades seismicity raised in the vicinity of the natural gas fields. Due to the spatial vicinity of the earthquakes to the operated natural gas fields and their appearance starting after the beginning of extraction they are ranked as induced events. Altogether, 47 events with ML 0.5 to 4.5 were detected between 1977 and 2014. Whereas epicenters can be determined with high accuracy, other source parameters, such as focal depths and focal mechanisms, are of lower accuracy. This is mainly caused by the sparse station coverage in the area and relatively bad signal-to-noise conditions as a result of thick sedimentary layers. The process of earthquake generation is still not well understood. We generally assume, that anthropogenic stress changes within the reservoir lead to the reactivation of prominent tectonic faults. The predominant cause for stress variations might be the large pore pressure reduction in the reservoir as a consequence of the gas extraction. We present focal mechanisms for 10 events with ML > 2.8 and invert the solutions for the regional stress field. The majority of the focal mechanisms represents normal faulting and exhibits NW-SE oriented nodal planes being in quite good agreement with the strike direction of nearby tectonic faults. In our presentation we compare the focal mechanisms of the induced events of Northern Germany with mechanisms of the natural gas fields in the Netherlands and with the few mechanisms for the rare tectonic events in the area. The stress field calculated on the base of the induced events is compared with stress data in the European Stress Map for Northern Germany.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-471

Interferometric location of microseismic events induced by gas storage operations

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Underground gas storage is a common industrial operation that consist in the injection of natural gas in aquifers or depleted hydrocarbon reservoirs. Although these operations rarely stimulated seismicity, a recent case at the Castor platform in the offshore Spain was accompanied by a significant seismic sequence, culminated with a magnitude Mw 4.3 earthquake. In many cases, the lack of local microseismic monitoring networks limits the performance of the standard data analysis procedures, thus non conventional methods need to be established. We extend here the analysis of triggered seismicity related to gas injection at the Castor platform, in September-October 2013, where standard location procedures failed for magnitudes below Ml 2. We relocate these events using an interferometry based location method (Snieder et al., 2005). This technique exploits slight changes in the coda waves between two seismic events within a cluster. We proof that microseismic events can be classified in different families by combining a waveform correlation analysis and a clustering technique. Clustered events are characterized by a high similarity of waveforms, which implies a similarity in both source mechanism and location. In these conditions, the analysis of seismic coda recorded at a single receiver can be used to infer a measure of the spatial separation between two seismic sources. Absolute locations can be then retrieved by considering all interevent distances, a procedure which requires at least three reference locations. We discuss the potential of the coda interferometry location approach to monitor induced seismicity, by relocating about 1000 seismic events induced by gas injection operations in Spain. Results are used to discuss the possible proposed faults scenarios.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-472

The baseline background seismicity of the Sulcis basin coalfield (Sardinia, Italy) from a temporary passive seismic experiment

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The Sulcis carboniferous basin (Sardinia Island, Italy) is the most coalfield existing within the Italian territory, discontinuously exploited from 1889 to 1972.
The Sulcis basin was selected as a test site for a CO_2 capture and sequestration pilot-project. This project was carried out by the Sotacarbo S.p.A. company and funded by both Italian Ministry of Economic Development and Sardinia Region Government.The goal of this project is to evaluate the possibility to apply the technology for CO_2 geological storage in saline aquifer, located under the coal seams. As a matter of facts, the basin seems to be characterized by a storage capacity for the saline aquifer of about 30 Mt of CO_2.
The Sulcis basin area shows no instrumental seismicity for the 1981-2014 period, even if historical seismicity catalogues report two events in 1771, with M3.0 and M3.5, both occurred in the Sant'Antioco island area. In this context a temporary seismic network of stations have been deployed to better characterize the seismic baseline of the whole Sulcis basin and surrounding areas.

The passive seismic experiment, started from July 2014, is still ongoing and it will end in July 2015: 10 seismic acquisition systems have been designed into a network with an average distance of 8-10 km between each other. 8 stations are equipped with a 24-bit, 6 channels digitizer and a 3-components long period (5s.) seismic sensor, while the others were deployed at the NE and SE border of the study area, featured by broadband seismic sensors (120 s.)

In this work we present the preliminary results of the seismic passive experiment, the analysis of the recorded data, the seismic network performances assessment, as

well as the whole Sardinia seismic monitoring improvement produced by the analysis of such datasets.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-473

Multiparametric station: Electric, magnetic, seismic, radon gas and GNSS data measurements on the central region of Colombia

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The tectonic convergence process, which takes place in the north-west part of South America, due to Nazca, Cocos, South American and Caribbean Plates interaction has been aim of study with different methods; however, most of them have been applied one after another, but not simultaneously, resulting on an extended in time set of data, but, which includes contributions from different methods applied in different time periods.

Such methods have been applied in the central region of Colombia, particularly in the Piedmont of the Eastern Cordillera. This region is of great interest because of the significant race of the number of seismic events of different magnitudes in recent times. This phenomenon requires additional studies in order to clarify, which is the influence of the particular natural tectonic processes, and, which the intense petroleum exploitation activity developed nowadays.

A number of multiparametric stations are being deployed in the central region of Colombia. The measurements are beginning to provide electric, magnetic, seismic, radon gas, and GNSS data. Here we will show the preliminary results of instrumental deployment, as well as, we will discuss the repercussion of the intense petroleum exploitation activity developed nowadays in the Piedmont of the Eastern Cordillera in Colombia.

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IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-474

Time-lapse seismic tomography using the data of microseismic monitoring network in Pyhäsalmi mine (Finland)

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We present results of a seismic travel-time tomography applied to microseismic data from the Pyhäsalmi mine, Finland. The data about microseismic events in the mine is recorded since 2002 when the passive microseismic monitoring network was installed in the mine. Since that over 100000 microseismic events have been observed. One of the purposes of our study was to test how the travel-time tomography works with the passive microseismic monitoring data where the source-receiver geometry is based on non-even distribution of natural events in the mine and hence, is a non-ideal one for the travel-time tomography. The tomographic inversion procedure was tested with the synthetic data and real source-receiver geometry and with the real travel-time data of the first arrivals of P-waves from the microseismic events. The results showed that seismic tomography is capable to reveal differences in seismic velocities in the mine area corresponding to different rock types, for example, the velocity contrast between the ore body and surrounding rock. The velocity model recovered corresponds well to the known geological structures in the mine area. The second target was to apply the travel-time tomography to microseismic monitoring data recorded during different time periods in order to track temporal changes in seismic velocities within the mining area as the excavation proceeds. The result shows that such a time-lapse travel-time tomography can recover such changes. In order to obtain good ray coverage and good resolution, the time interval for a single tomography round need to be selected taking into account the number of events and their spatial distribution.

Acknowledgements: This study has been supported by ERDF SEISLAB project and Pyhäsalmi Mine Oy.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-475

Seismic activity of developing sinkhole in Solikamsk-2 salt mine , Russia

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Since 2006 at Upper Kama potash deposit a period of multiple underground karst caves transforming quickly into sinkholes has begun. All of them are under observation with local seismic networks, counting up to 6 stations per object and providing data about negative changes in undermined massif. Such observation was initiated in 1995 when strong 3.8 Ms earthquake in Solikamsk-2 mine happened. That event was a result of pillar destruction on 600x600 m area. It was sensed as far as 20 km and had severe consequences in mine that was meant to lead to soon mine flooding. After the earthquake a subsidence zone of the same size and depth of 4.5 m had appeared on the surface. But during following almost 20 years the mine had continuing to work without some serious problems. The main problem has become obvious only on 18 November 2014 when 20x30 m sinkhole appeared in South-Eastern part of roof fall zone. Its appearance was accompanied with significant (hundreds times) rise in seismic activity in advance (2 months).

The Solikamsk-2 mine area under seismic control is about 50 km^2, but early activity of local destruction processes inside earthquake source zone were discovered very accurately in 1 day after their beginning (8 September 2014). We had enough time to install around the zone additional 6 seismic stations and to descry developing sinkhole in details till now. We applied for monitoring our experience obtained earlier at flooded Berezniki-1 mine where at the moment one can count 3 existing sinkholes and 5 potentially hazard zones.

The results of observation are agreed with taken seismic model of developing karst caves in salt mines. Also they provide early warning in zone under control where a lot of measures and works are carried out to limit negative consequences in mine.

IASPEI (Seismology, Geophysics)

S01cp - S01c Seismological Observation and Interpretation: Triggered and Induced Seismicity

S01cp-476

Reservoir-Triggered Seismicity in Brazil: Characteristics and possible new cases

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We report 23 cases of reservoir-triggered seismicity (RTS) in Brazil, emphasizing cases observed in the last few years. In worldwide terms Brazil presents a relatively high number of RTS. Nevertheless if we consider the Brazilian number of reservoirs with water level above 30 m high this number of RTS is not so expressive. Studies on RTS in Brazil have been made for about 40 years and nowadays almost all the largest Brazilian reservoirs have seismic is seismically monitored.

Two magnitudes 4 RTS earthquakes were observed, the biggest 4.2 m_b (MMI VI). About 70% of the RTS cases present initial seismicity (the events occur less than 1~2 years after the first impoundment).

In Brazil, the magnitudes of triggered event are not directly proportional to the depth of the water column or to the total volume of the reservoir, although, the RTS has been more common in reservoirs with depth > 100 m (about a half of the cases). However, there are reservoirs higher than 100 meters that never had presented RTS and others with height less than 50 m with triggered seismicity.

The RTS earthquakes in Brazil despite being associated in many cases, about 40%, with shallow reservoirs (< 50 m), these have significant magnitudes of the main event ($M \geq 3$), and conversely some large reservoirs (depth greater than 100 m or volume greater than 2 km^3) have presented expressionless RTS main event ($M \leq 2$).

In this work we will discuss the Brazilian RTS features, highlighting cases not yet reported.

IASPEI (Seismology, Geophysics)

S01da - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-1945

Historical earthquake studies and document database in Japan

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Damage and other effects from past earthquakes and tsunamis have been recorded in historical documents and preserved. Compilation of such historical earthquake documents started in the early 20th century and 33 volumes of historical document sourcebooks (about 27,000 pages) have been published. However, these sourcebooks are not in digital form and contain documents with various reliabilities, hence have been used by only limited researchers. In the last decade, efforts to make full-text digital database with evaluation of document reliability have started. For earthquakes from the beginning of the 7th century to the early 17th century, "Online Database of Historical Documents in Japanese Earthquakes and Eruptions in the Ancient and Medieval Ages" (Ishibashi, 2009) has been already constructed and publicized. They investigated the sourcebooks or original texts of historical literature, emended the descriptions, and assigned the reliability of each historical document on the basis of written dates. For the Edo period (from the beginning of the 17th century to the middle of the 19th century), the number of historical document had dramatically increased throughout Japan, hence collections of documents and construction of database are still in progress. A database was constructed for seven damaging earthquakes along the Sea of Japan coast, and another one is under construction for those earthquakes around Tokyo. These databases, with another database for liquefaction traces would be utilized to estimate the distributions of seismic intensities and tsunami heights.

IASPEI (Seismology, Geophysics)

S01da - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-2273

Macroseismic Survey of the ML5.5, 2014 Orkney Earthquake

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On 5 August 2014 at 12:22 hours (local time), an earthquake of local magnitude M_L = 5.5 occurred in the Orkney area in the North West Province, South Africa. The earthquake shaking was felt widely in South Africa as far as Cape Town as well as in Maputo, Mozambique and Gaborone in Botswana. One person was killed when a wall collapsed on him and more than 600 houses were damaged. Following the earthquake, many people submitted reports to the Council for Geoscience through the online questionnaire which recorded their experience, whilst others reported the event and its effects on social networks like twitter and in newspapers. The Council for Geoscience also sent out a team of scientists to further assess the effects of the event in the community by interviewing members of the public and completing additional questionnaires. A total of 866 observations were collected. Analysis of the collected macroseismic data produced 170 intensity data points which showed that a maximum intensity of VII was experienced in communities located in the epicentral area. Further analysis and research were conducted to try and understand the source of this earthquake. This included the determination of the fault plane solution, which showed that the event was created by strike – slip faulting. Airborne geophysical data were also used to identify the fault along which the earthquake occurred. This was necessary as there was no surface expression of the earthquake and no previously identified fault near the epicentre. The interpretation of the data showed a fault located about 500m from the epicentre appearing to form an boundary to the east of located aftershocks.

IASPEI (Seismology, Geophysics)

S01da - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-3295

Intensity data and macroseismic maps of earthquakes in southwestern Germany

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Earthquake hazard in Germany is to a large part located in the southwest of the country, thus the Federal State of Baden-Württemberg is particularly affected by earthquakes. Seismicity is highest along the Upper Rhine Graben and in the region of Albstadt on the Swabian Jura. Since the occurrence of the 1911 earthquake (intensity VIII), the Albstadt region has become one of the seismically most active source regions north of the Alps. In an ongoing project a systematic search for information about historical earthquakes in Baden-Württemberg is carried out tracing back information to the primary sources. We were successful in finding contemporary sources from the 17th and 18th century, which include earthquake information even of lower intensities (III to IV). Some sources document earthquakes that have been unknown so far. Especially diaries and reports of civil servants turned out to be valuable and detailed historical sources. A data base hosts all our catalogue data, including macroseismic intensities and information about corresponding documents. Existing regional catalogue subsets have been reviewed and included into the data base. Relevant parts of national catalogues (BGR catalogue for Germany, ECOS for Switzerland and SISFRANCE for France) have been implemented as well. About 250 macroseismic maps from the archives and various other sources have now been published in the monograph “Macroseismic atlas Baden-Württemberg – 19th and 20th century”. Intensity data points (IDP) in digital form, however, are still missing to a large extent. We have started to acquire digital IDPs from the original macroseismic questionnaires, from earlier publications and from own assessments. First results of IDP data are presented and compared with contemporary macroseismic maps.

IASPEI (Seismology, Geophysics)

S01da - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-4428

Maximum observed intensity map for the azores (Portugal) - preliminary results

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The Azores archipelago is a seismic active region including nine inhabited islands. Since its settlement in theXVth century, the archipelago has been stricken by 33 earthquakes with intensity ≥ VII. We propose the firstmaximum observed intensity (MOI) map for this region in order to identify areas where high magnitude eventsoccurred in the past.The maximum intensity of each event ≥ V is selected from the recorded earthquake catalogue (period of thecatalogue). Fourteen historical events with intensities ≥VII that occurred between 1522 and 1912 were added.Clustered earthquakes associated with volcanic eruptions (1957/58 and 1964) as well as aftershocks that lastedseveral months were removed in order to avoid biases. In order to create the MOI map, the kriging method is usedto interpolate existing data to a regular grid of point .The MOI map shows that the eastern part of São Jorge and Graciosa Island have the highest intensity values ofXI and IX respectively. In the Terceira Island, intensity VIII are observed in the eastern and western part. In FaialIsland, intensity X is in a stripe with direction NW-SE. In Pico, the maximum intensities (VII) are on the easternand western edges of the island. In São Islands, few zones of high intensities (X and VII) are shown in the western,southeastern and northern parts. In Santa Maria Island, the eastern part has the highest intensity (VI). We do notpresent results of Flores and Corvo Islands because the seismicity is very low and does not match with our criteriaof events with intensity ≥ V. Finally, it could noticed that such a map does not discriminate site effects as if itshows areas with highest strong ground motion.

IASPEI (Seismology, Geophysics)

S01db - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-1201

A statistical approach for determination of sourceparameters of historical earthquakes from historicalseismic damage records

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Large earthquakes have long recurrence intervals. It is crucial to consider long-time seismicity for a proper assessment of potential seismic hazards. It is required to use historical earthquake records to complement the long-time seismicity records. Historical earthquake records remain as in seismic damage description with limited accuracy in source parameters including event location and its size. It is important to determine epicenters and magnitudes of historical earthquakes accurately. A noble method to determine the event location and magnitude from historical seismic damage records is introduced. Seismic damage is typically proportional to the event magnitude, and is inversely proportional to the distance. This feature allows us to deduce the event magnitude and location from spatial distribution of seismic intensities. However, the magnitude and distance trade off each other, inhibiting unique determination of event magnitude and location. The Gutenberg-Richter frequency-magnitude relationship is additionally considered to constrain the source parameters. The Gutenberg-Richter frequency-magnitude relationship is assumed to be consistent between instrumental and historical seismicity. A set of event location and magnitude that satisfy the chance of of event occurrence according to the Gutenberg-Richter frequency-magnitude relationship is selected. The accuracy of the method is tested for synthetic data sets, and the validity of the method is examined. The synthetic tests present high accuracy of the method. The method is applied to historical seismic damage records, which allows us to calibrate the source parameters of historical earthquakes.

IASPEI (Seismology, Geophysics)

S01db - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-2131

Historical earthquakes attested to by sparse data: can the epicentre be determined?

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Macroseismic data sets collected after modern earthquakes are often large and, even if not, the determined macroseismic epicentre can be compared with the instrumental one in order to obtain further information. In contrast, macroseismic data sets related to historical earthquakes are often sparse, and there is no instrumental epicentre available. It is well recognized that the uncertainties associated with epicentres of historical earthquakes can be large, but it is difficult to quantify them using real data. Therefore synthetic sets of Intensity Data Points are used in this study. Only small data sets are investigated. It is monitored how the properties of the data sets affect the uncertainty of the epicentre location. It is attempted to define the criteria for successful and unsuccessful epicentre location.

IASPEI (Seismology, Geophysics)

S01db - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-2601

Historical earthquakes and the problem of catalogue completeness

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A necessary task in probabilistic seismic hazard assessment is estimating the completeness of the historical earthquake record. While there are standard techniques for estimating this statistically for well-populated (chiefly modern) earthquake catalogues, there is less discussion in the literature of how to derive limiting values for large early events. Historical earthquakes that are very poorly documented are useful in this respect. If the data for such events are inadequate for reasonable parameterisation, they are effectively “missing” from the catalogue; yet they are known to have occurred, and may be a useful correction to overly-optimistic estimates of catalogue completeness. Some examples will be presented from Britain of poorly-known earthquakes in the medieval and early modern period that set limits on estimates of catalogue completeness.

IASPEI (Seismology, Geophysics)

S01db - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-4068

New insights on pre-1900 great earthquakes along the Peru-Chile trench

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The aim of our work is to improve the knowledge of the great ($M \geq 7$) subduction earthquakes occurred along the Peru and Chile trench before the year 1900. We first analysed the studies made available in the Global Historical Earthquake Archive - GHEA (http://www.emidius.eu/GEH/), and crosschecked them in order to critically evaluate and improve the data supporting each earthquake. The available macroseismic data were also checked and improved and then used to assess homogeneous parameters. For this purpose we derived a new relation describing the attenuation of macroseismic intensity with distance, specific for subduction earthquakes in the area, based on a revised set of instrumentally recorded earthquakes from the ISC-GEM Catalogue (http://www.isc.ac.uk/iscgem) and the related macroseismic data from the CERESIS database (www.ceresis.org).

The new magnitude, location, and - especially - hypocentral depth of the considered earthquakes have been matched with the geometry and characteristics of the subduction plane, in order to check their consistency and to infer the possible geometry of the individual seismogenic sources. The revised earthquake parameters for pre-1900 earthquakes allowed us to re-evaluate the long-term seismic behaviour of the Peru-Chile subduction zone in terms of recurrence intervals and seismic moment release.

IASPEI (Seismology, Geophysics)

S01db - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

IUGG-5020

Calculation of historical earthquake magnitudes in Greece from empirical magnitude/intensity relations

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The seismicity of Greece is very high with an average rate of at least 1 event/yr for earthquakes of magnitude 6 or over. Thanks to the long history of the country hundreds of historical earthquakes were documented. Several descriptive and parametric catalogues of the Greek historical seismicity have been published. However, in parametric catalogues the calculation of earthquake magnitudes is not well supported, thus leaving this issue open for re-examination. In this contribution earthquake magnitudes were determined from empirical relations between surface-wave magnitude, Ms, and maximum intensity, Imax, found for Greek earthquakes occurring during the instrumental period of seismicity, namely from 1911 to 2005. Two groups of empirical relations were established based on linear regressions of Imax on Ms, as well as of log (Ai) on Ms; where Ai is the area of perceptibility of intensity degree i. For both groups, relations for inland, coastal, offshore and all earthquakes were developed. Inland earthquakes have epicentral distance, Δ, more than 20 km inland from the closest sea-shore, while coastal earthquakes have Δ up to 20 km either inland or offshore from the closest sea-shore. The method was applied to a long number of surface historical earthquake events occurring in the Hellenic arc. For each event at least one relation of each one of the two groups was applied and the average magnitude was adopted. To check the good performance of the method the rates of historical events in certain magnitude ranges were compared with the rates of instrumental earthquakes. Also, earthquake magnitudes of the period 2006-2014 were calculated with the method proposed and compared with the measured ones. The results indicate that the method works quite well.

IASPEI (Seismology, Geophysics)

S01dp - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

S01dp-571

OSL dating of the Ira trench site in the easternmost part of the NTF, where it joins the EMF

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OSL dating of the Ira trench site in the easternmost part of the NTF, where it joins the EMF

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Abstract

The Eastern Mosha Fault (EMF) and the North Tehran Fault (NTF) are two major active faults of the southern central Alborz Mountains, located in proximity of Tehran. The Ira site is in a point where, the surface trace of NTF joins the EMF and reveals the history of interaction between rock avalanches, active faulting and sag-pond development. Twelve OSL samples were collected by inserting 50-mm-diameter stainless steel tubes into paleoseismological units.

Equivalent dose values were measured on quartz by using large aliquots. This presentation demonstrates the OSL behaviour of each sample including the representative OSL decay curves, and growth curves and explain why while only limited replicates for each sample were used for age determination many more aliquots were measured to achieve this. The effect of incomplete bleaching of the

sediment during the last period of transport or exposure and different statistical models that were employed for age determination will be discussed.

Seven OSL samples yielded mostly old ages, widely spaced in time, therefore not suitable for estimating the more recent recurrence history of the earthquakes. In the end a brief interpretation of event history in the Ira trench site, will be presented.

IASPEI (Seismology, Geophysics)

S01dp - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

S01dp-573

The characteristic of the damage from historical large earthquakes in Kyoto

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The Kyoto city, which is located in the northern part of Kyoto basin, has a long history with >1200 yr since the city was initially constructed. The city has been a populated area with many buildings and the center of the politics, the economy and the culture in Japan for nearly 1,000 years. The Kyoto city experienced six damaging large earthquakes during historical ages: i.e., in 976, 1185, 1449, 1596, 1662, and 1830. Among them, the last three large earthquakes which caused severe damage in Kyoto occurred during the period in which the city area had expanded. All of these earthquakes are considered to be the inland earthquake which occurred around Kyoto basin. The damage distribution in Kyoto from historical large earthquakes is strongly controlled by ground condition and earthquakes resistance of buildings rather than distance from estimated source fault. Therefore, we need to consider the condition of building such as elapsed years since the construction or last repair as well as the strength of ground shaking to more accurately and reliably estimate seismic intensity from historical earthquakes in Kyoto.

IASPEI (Seismology, Geophysics)

S01dp - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

S01dp-574

Three damaging earthquakes around Edo-Tokyo recorded in historical documents:The 1703 Genroku-Kanto, 1855 Ansei-Edo, and 1923 Taisho-Kanto earthquakes

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Three historical earthquakes which caused significant damage to Edo (present day Tokyo) and Tokyo are the 1703 Genroku Kanto, 1855 Ansei Edo, and 1923 Taisho Kanto earthquakes. We investigate and show the damage from these earthquakes on the basis of historical documents.
The 1923 Kanto earthquake and subsequent massive fire caused more than 100,000 casualties. We found a document which describes evacuation of people from severely damaged areas such as Tokyo and Yokohama to neighboring Chiba prefecture, and their life in displaced places. Documents in elementary schools in Kimitsu City, Chiba prefecture recorded the damage to the schools and their reactions after the earthquake.
The 1703 Genroku Kanto earthquake is considered to be the penultimate Kanto earthquake. Coastal uplift and subsidence along the coast of Boso peninsula are described in historical documents. For example, there is a picture drawing coastal subsidence by the mainshock in Yoshihama coast of Kyonan Town, Chiba prefecture. This earthquake generated a large tsunami, with a height of 5 m, especially along the Kuju-kuri coast, Pacific coast of Boso peninsula. We found that the tsunami also reached to Edo, on the innermost section of Tokyo Bay, and caused casualties.
The 1855 Ansei Edo earthquake occurred at the end of Edo period and caused ~7,000 casualties. Unlike the Kanto earthquake, this earthquake occurred just below Edo and detailed damage distribution in Edo has been investigated from numerous documents and picture materials such as 'Ansei Kenmonshi' and catfish pictures. We found that some damage, such as a collapse of stone monuments, has been documented in southern Boso peninsula, about 75 km south of Edo.

IASPEI (Seismology, Geophysics)

S01dp - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

S01dp-575

Macroseismic intensity investigation of the November, 2014 M=5.7 Vrancea crustal earthquake

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An M_L=5.7 crustal earthquake occurred in the area of Marasesti city of Vrancea county (Romania) at 21:14:17 local hour (19:14:17 GMT) on November 22, 2014- the epicenter was located at north latitude 45.87° and east longitude 27.16°, with a focal depth of 39 km. This earthquake is the main shock of an sequence that started with this. During the sequence, characterized by absence of foreshocks, a total of 75 earthquakes were recorded in 72 hours, the largest of which occurred in the same day of the main shock, at 22:30 (M_L= 3.1). The crustal seismicity of Vrancea seismogenic region is characterized by moderate earthquakes with magnitudes that have not exceeded M_W 5.9, with this value being assigned to an earthquake that occurred in historical times on March 1, 1894 (Romplus catalog). Soon after the earthquake occurrence, in order to define the macroseismic field of ground shaking, the NIEP sent macroseismic questionnaires in all affected areas, to be able to assign macroseismic intensities. The General Inspectorate for Emergency has helped us in the collection of the information related to earthquake effects. Through this organization it was facilitated the access to the communes and towns municipalities in the areas where the earthquake was felt, the mayors having the task to distribute these questionnaires to the population. According to macroseismic questionnaires survey in the felt region, the intensity of epicentral area reached VI MSK, and the seismic event was felt in all the extra-Carpathian area. This earthquake caused general panic and minor to moderate damage to the buildings in the epicentral area and the northeast part of country. The main purpose of this paper is to present the macroseismic map of the earthquake based on the MSK-64 intensity scale.

IASPEI (Seismology, Geophysics)

S01dp - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

S01dp-576

"Source parameters of the large historical earthquakes in the Tien-Shan region: Investigation results by analogue teleseismic records."

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Instrumental seismology started developing significantly at the end of the 19th century which resulted in the first global seismic network consisting of more than a 100 seismic stations distributed worldwide in early of the 1900s. Early seismograms were recorded on a paper, which makes them very brittle, thus many historical seismic records were lost or considerably damaged. Those which survived are widely distributed in different archives worldwide and require very particular effort for their analysis. There have been several studies pointing out the value of historical seismograms and the necessity of their preservation. However the number of detailed studies of the historical earthquake source parameters with modern techniques is limited. These can be explained by the difficulties arising from collecting and digitizing the historical records, which is very time consuming complicated process.

The presented study aims to determine source parameters of several large (M>7) earthquakes which occurred between1902 and 1970 in Tien-Shan region, including well known the Chon-Kemin and the Sarez-Pamir earthquakes. The seismic records from different seismic stations worldwide for five earthquakes were collected, scanned and digitized. The digitized seismic records were used to: relocate the earthquake epicenters; recalculate their magnitude (mB, Ms, Mw); and redefine the depth, these newly defined parameters often differed from previously reported values. Additionally the focal mechanisms of the earthquakes were determined by amplitude ratios comparison and forward waveform modeling, the fault orientation and the depth were constrained, and the seismic moment of the earthquakes was estimated.

IASPEI (Seismology, Geophysics)

S01dp - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

S01dp-577

Conclusions reached from environmental effects of historical earthquakes occurred in the Pannonian Basin

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Macroseismic observations and contemporary records are the only primary information to reconstruct hypocenter data and shaking intensity in case of historical earthquakes. Previously attention has been paid mainly to the analysis of effects on humans and manmade structures. During this research we have focused on the environmental effects, especially on soil liquefaction caused by stronger historical earthquakes.
Most part of Hungary are low-lying plains covered by young Holocene fluvial sediments with high ground water level. Consequently, the area is susceptible to development of liquefaction. Despite the moderate seismicity, several liquefaction cases have been documented during larger (M5.4-6.3) historical earthquakes, for example in Komárom (1763, 1783, 1822), Mór (1810), Érmellék (1829, 1834), Kecskemét (1911) and Dunaharaszti (1956). Most of the earthquakes listed occurred before the start of instrumental recordings.
We have studied spatial extension of surface manifestations of liquefaction on the basis of contemporary observations, as well as local subsoil conditions and ground water level. We have modelled horizontal ground accelerations possibly caused by these historical earthquakes using ShakeMap program.
In case of Komárom earthquake in 1763, epicentral intensity has been estimated on ESI 2007 scale and compared with other intensity estimates. Distribution of settlements where liquefaction was observed supports the assumption that the epicenter of the earthquake was probably located NW from Komárom as proposed earlier on the basis of the damage distribution.
We could identify some places where liquefaction occurred during the 1956 Dunaharaszti earthquake. On the basis of SPT and CPT measurements we have estimated the maximum surface acceleration.

ASPEI (Seismology, Geophysics)

S01dp - S01d Seismological Observation and Interpretation: Macroseismology and Historical Earthquakes

S01dp-578

Damage and seismic intensity distributions of the 1946 Nankai earthquake revealed by the reanalysis of questionnaire survey immediate the earthquake

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A questionnaire survey to investigate the strength of man-felt ground motion and earthquake induced damage of the 1946 Nankai earthquake (M 8.0) was performed immediately after the earthquake for 1,014 elementary schools in western Japan by the Earthquake Research Institute and the Department of Science of Tokyo Imperial University, but the results has not been published. We analyzed the questionnaire and summary sheets of the survey, and estimated the distributions of seismic intensity, various kinds of damage, and human behaviors.

The questionnaire consists of 28 questions and descriptions for seismic intensities on the modified Mercalli (MM) intensity scale. The maximum seismic intensity estimated from the damage of Japanese-style wooden houses reaches X-XI near the source-rupture area such as in the Shikoku Island and Wakayama and Okayama Prefectures. The damage rate of wooden houses was more serious in the plains and basins of populated cities than that in the mountainous regions. The expected seismic intensities from other damage (bridges, stone walls, underground pipes, etc.) also exceed X. The X or higher seismic intensities on MM-scale corresponds to VII on the Japan Meteorological Agency's intensity scale (JMA-scale), which was introduced only after the 1948 Fukui earthquake (M7.1). Therefore, the previously-estimated seismic intensity distribution of the 1946 earthquake on the JMA-scale may be underestimated. The questionnaire survey also shows that sand boils by liquefactions were generated in the Mie Prefecture even though it is locating relatively far from the 1946 source region.

Acknowledgement: This study was supported by the MEXT's "New disaster mitigation research project on Mega thrust earthquakes around Nankai/Ryukyu subduction zones".

IASPEI (Seismology, Geophysics)

S01ea - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-0769

A P-wave based methodology for rapid, real-time determination of seismic moment, fault extent and stress-drop

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The source characterization for earthquake early warning systems is generally based on the measurement of the peak amplitude or period parameters measured along the early portion of the recorded P and S-wave signals (3 or 4 seconds). These parameters are related to the earthquake size or to the peak ground shaking amplitude through empirical scaling relationships. Standard methodologies for real-time applications typically assume a point-source model of the earthquake source and this assumption may be inadequate to describe the source of large earthquakes, possibly introducing significant biases in the real-time estimation of earthquake magnitude and ground shaking prediction. To avoid magnitude underestimation, the use of limited time windows has been recently replaced by the concept of expanding time windows, showing that standard parameters and existing empirical relationships can be used also for very large earthquakes, provided that appropriate time windows are selected for the parameter measurement. Following the concept of expanding P-wave time windows, here we propose a straightforward methodology, based on the P-wave amplitude, to quickly characterize the finite extension of the seismic source and its scalar moment. In particular, here we investigate whether and how the progressive and evolutionary measurement of early warning parameters can provide a rapid estimate of the event magnitude and of the expected length of the rupture. The methodology we propose is computationally simple and does not require complex signal processing. It is expected to provide a rapid and robust estimation of the source extent, which can significantly improve the accuracy of the ground shaking prediction during the occurrence of very large events.

IASPEI (Seismology, Geophysics)

S01ea - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-1244

Multi-events earthquake early warning algorithm using a Bayesian approach

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Current earthquake early warning (EEW) systems lack the ability to appropriately handle multiple concurrent earthquakes, which led to many false alarms during the 2011 Tohoku earthquake sequence in Japan. This research uses a Bayesian probabilistic approach to handle multiple concurrent events for EEW. We integrates P-wave picking time and maximum displacement amplitude from both JMA and Hi-net seismic stations into a single algorithm. Importance Sampling method with a sequential proposal probability density function is used to estimate the earthquake parameters, i.e., hypocenter location, origin time, magnitude and local seismic intensity. A real data example based on two months data (March 9 to April 30, 2011) around the time of the 2011 M9 Tohoku earthquake is studied to verify the proposed algorithm. Our algorithm results in over 90% reduction in the number of incorrect warnings compared to the existing EEW system operating in Japan.

IASPEI (Seismology, Geophysics)

S01ea - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-1301

Advanced moment-tensor inversion code

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Focal mechanisms are important for understanding seismotectonics of a region, and they serve as a basic input for seismic hazard assessment. Usually, the point source approximation and the moment tensor (MT) are used. We are developing a new, fully automated tool for MT inversion taking into account recent developments in the field. It includes automated data retrieval, data selection according to noise level and presence of various instrumental disturbances, and setting frequency ranges for each station according to its distance, noise, and event magnitude. The MT inverse problem is solved in a space-time grid whose size is automatically chosen according to the location uncertainty and magnitude. Green's functions are calculated in parallel. The software enables to invert just waveforms or waveforms together with first-motion polarities. Simultaneously with the MT solution and evaluation of L2 misfit, the uncertainty and reliability of the result is also evaluated using condition number and 6D moment-tensor error ellipsoid. The software is tested on a dataset from the Swiss seismic network and the results are compared with the existing high-quality MT catalog. The software is programmed as much versatile as possible in order to be applicable in other regions and for events ranging from local to regional. It shares some similarities with the broadly used ISOLA software in terms of the inversion methods and input/output file structures, but most codes have been re-written from the scratch for maximum computational efficiency. Opposed to ISOLA, whose advantage is in a friendly manual processing of individual events using Matlab GUI, the new codes are intended rather for (i) massive automated application on large sets of earthquakes and/or (ii) near real-time applications.

IASPEI (Seismology, Geophysics)

S01ea - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-1662

Numerical shake prediction for Earthquake Early Warning: data assimilation, real-time shake-mapping, and simulation of wave propagation

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Many of the present Earthquake Early Warning (EEW) systems quickly determine the hypocenter and magnitude, and then predict strengths of ground motions. The 2011 Tohoku Earthquake (M_W9.0), however, revealed some technical issues with such methods: under-prediction at large distance due to the large extent of the fault rupture, and over-prediction because the system confused by multiple aftershocks that occurred simultaneously. To address these issues, we propose a new concept for EEW, in which the distribution of the present wavefield is estimated precisely in real time (real-time shake mapping) by applying data assimilation technique, and then future wavefield is predicted time-evolutionally using physical process of seismic wave propagation. Information of hypocenter location and magnitude are not required, which is basically different from the conventional method.

The proposed method is applied to the 2011 Tohoku Earthquake (M_W9.0) and the 2004 Mid-Niigata earthquake (Mw6.7). Future wavefield is precisely predicted, and the prediction is improved with shortening the lead time: for example, the error of 10 s prediction is smaller than that of 20 s, and that of 5 s is much smaller. By introducing this method, it becomes possible to predict ground motion precisely even for cases of the large extent of fault rupture and the multiple simultaneous earthquakes.

The proposed method is based on a simulation of physical process from the precisely estimated present condition. We call this method “numerical shake prediction” by analogy to “numerical weather prediction” in meteorology.

IASPEI (Seismology, Geophysics)

S01ea - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-4108

Field installation and real-time data processing of the new integrated seismogeodetic system with real-time acceleration and displacement measurements for EEWS

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We will discuss and show the results obtained from an integrated SeismoGeodetic System, model SG160-09, installed in the Chilean National Network. The SG160-09 combines seismic recording with GNSS geodetic measurement in a single compact package. The receiver incorporates on-board GNSS point positioning using Real-Time Precise Point Positioning (PPP) technology with satellite clock and orbit corrections delivered over IP networks. The seismic recording element includes an ANSS Class A, force balance triaxial accelerometer with the latest 24-bit A/D converter. The SG160-09 processor acquires and packetizes both seismic and geodetic data and transmits it to the central station using an advanced, error-correction protocol with back fill capability.

The SG160-09 has been installed in the seismic station close to the area of the M8.2 Iquique earthquake of April 1, 2014, in northern Chile, a seismically prone area at the current time. The hardware includes the SG160-09 system, external Zephyr Geodetic-2 GNSS antenna, and high-speed Internet communication media. Both acceleration and displacement data was transmitted in real-time to the National Seismological Center in Santiago for real-time data processing using Earthworm / Early Bird. Data from the SG160-09 system was used for seismic event characterization along with data from traditional stand-alone broadband seismic and geodetic stations installed in the network.

Our presentation will focus on the key improvements of the network installation with the SG160-09 system, rapid data transmission, and real-time data processing for strong seismic events and aftershock characterization as well as advanced features of the SG160-09 for Earthquake and Tsunami Early Warning system.

IASPEI (Seismology, Geophysics)

S01ea - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-4301

Scaling of amplitude and energy early warning parameters for Iquique, Northern Chile: Implications for future large subduction earthquakes

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We studied the nucleation process of Northern Chile events that included the large earthquakes of Tocopilla 2007 Mw 7.8 and Iquique 2014 Mw 8.1, as well as the background seismicity recorded from 2011 to 2013. We built a seismic catalogue of almost 400 events. We re-located and computed moment magnitude for each event. We also computed Early Warning (EW) parameters - Pd, Pv and IV2 - for each event. We find that Pd, Pv and IV2 are good estimators of magnitude for interplate thrust and intraplate intermediate depth events with Mw between 4.0 and 6.0. However, the larger magnitude events show a saturation of the EW parameters.

The Tocopilla 2007 and Iquique 2014 earthquake sequences were studied in detail. Almost all events with Mw>6.0 present precursory signals so that the largest amplitudes occur several seconds after the first P wave arrival. The recent Mw 8.1 Iquique 2014 earthquake was preceded by low amplitude P waves for 20 s before the main asperity was broken. The magnitude estimation can improve if we consider longer P wave windows in the estimation of EW parameters. There was, however, a practical limit during the Iquique earthquake because the first S waves arrived before the arrival of the P waves from the main rupture. The complex nucleation process observed by Iquique earthquake shows the difficulty to scale the EW parameters of small to large events using only the first seconds.

IASPEI (Seismology, Geophysics)

S01eb - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-0729

Rapid and concurrent Epi- & Hypocenter localisation for tracking earthquakes in real-time upon their initial detection

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This paper reviews several prior papers and two reports that incorporate work done in the development of an algorithm which is to rapidly evolve an increasingly accurate and concurrent localization of the Epicenter and Hypocenter of an Earthquake in real-time. This algorithm is an “interpolative tabular scan” whose tables are generated by P2P (point-to-point) ray tracers, using any radial Earth velocity model. The P2P tracers and velocity models are parametric to this process. The tables are matrices and lie in a 2-space dimensioned by depth (of emission source) and colatitude (of the surface arrival points). The pole for the set of colatitudes is oriented vertically above the Earthquake event. The requirement for this algorithm defines a physical system consisting of a network of stations any of which would communicate an onset time to a central facility. As these reports accumulate the localization of an Epi- & Hypocentes for the event can evolve. It is possible to eliminate “bad” or “unassociated” data from any set of onset timings by applying Chauvenet’s criterion for outlier rejection. The algorithm also supplies a set of take-off angles. On a 3.2 GHz processor the timings for groups of 5 to 8 stations start at ca. 0.7 s/station and increase to ca. 1.3 s/station for groups of up to 30 stations. This algorithm is seen as a front-end process for an Earthquake Early Warning (EEW) system so that more rigorous processes can be initiated once basic source localizations have been made. Tsunami alerts would be considered if any localization by the algorithm was found to be a maritime position.

IASPEI (Seismology, Geophysics)

S01eb - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-1822

Synthetic seismograms from a 3D crustal model for SW Iberia

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The Iberian Peninsula is characterized by a moderate seismic activity with large earthquakes separated by very long time intervals. The last large earthquakes have occurred at historical period, such as the 1755 earthquake Lisbon (I_{max}=X) or analogical instrumental (1969 Saint Vicente Cape shock, Ms=8.1). In consequence, there is a lack of broad-band digital records for large earthquakes at this region, which are necessary to develop an Earthquake Early Warning System (EEWS). In order to solve this problem, we have generated synthetic seismograms for earthquakes with magnitudes 6.0-8.0 at regional distances. Due to the heterogeneity of the region, we have used a 3D crustal model to generate the Green functions. To test the crustal model and to separate path effects from source effects, as first step, we model the 2007 (M_w=6.1) and 2009 (M_w=5.5) earthquakes, with very well know rupture process. Using the tested crustal model we generate synthetic seismograms using the wave propagation code e3D for largest shocks (range magnitudes 6.5 to 8.0) in order to estimate the theoretical PGV values. From these values and using the empirical correlations developed for this region, we obtain the I_{MM} and we compare them with observed intensities values.

IASPEI (Seismology, Geophysics)

S01eb - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-2538

"This is my abstract title"Application of the offshore real time monitoring data for disaster mitigation on seismogenic zones

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Lessons learnt from 2004 Sumatra Earthquakes and 2011 East Japan Earthquake 2011 accelerate deployments of ocean floor networks such as DONET, DONET2 and East Japan cable (S-Net). In the Nankai trough seismogenic zones, mega thrust earthquakes have occurred with the intervals of every 100-200 years.

Especially, in 1944/1946 Nankai Trough Earthquakes and 1854 Nankai Trough Earthquakes, these earthquakes occurred around the boundary of between the Tonankai and Nankai seismogenic zone.

DONET1 have deployed and DONET2 is under developing around the Nankai trough south western Japan. However, recurrence patters among these mega thrust earthquakes are quite different. Furthermore, these seismogenic zones are located near the coasts of southwestern Japan, so, evacuations from tsunamis are severe problems. Furthermore, the DONET1and DONET2 equipped with multi kinds of sensors such as seismometers and pressure gauges are very powerful and significant tools to monitor the broad band phenomena in seismogenic zones. The data from these ocean floor networks will be applied to the advanced early warning system of earthquakes and tsunamis, and the data assimilation for prediction research.

The new research project for the disaster mitigation on the Nankai Trough seismogenic zone are starting from 2013. In this project, disaster mitigation researches observation researches and simulation researches will be progressed and integrated. Especially, disaster mitigation researches are composed of civil engineering fields and social science fields.

IASPEI (Seismology, Geophysics)

S01eb - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-3179

Local heterogeneities disturb the empirical relationship between growth curves of initial P-wave and epicentral distances

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In the Earthquake Early Warning system (EEW), epicentral distance is estimated using amplitude growth rate of the initial P-wave. Empirically it has been adopted that the growth rate marks the specific value against a given epicentral distance. So the epicentral distance is inversely estimated from the growth rate using the empirical relationship. However the growth rates calculated from earthquakes having the same epicentral distance considerably scattered (sometimes 10^3 times) each other when the earthquakes locate at different regions. Qualitatively the difference in growth rates is due to variation in the local heterogeneities where the P-waves travel through. In this study we theoretically show that the amplitude growth rate is disturbed by variation in the local heterogeneities in the subsurface. First, we calculate theoretical scattered seismic waves (first-ordered PP, PS, SP and SS conversions) in heterogeneous medium, changing the parameter controlling the condition of heterogeneities, i.e., correlation distance. As a result, it is found that the amplitude growth rates at a given epicentral distance are largely scattered when the correlation distance is changed. Then, we calculate the spatial distribution of correlation distance which accounts the growth rate of earthquakes during 1997 – 2011 in Japan. The spatial distribution of correlation distance shows the same tendency with that of local heterogeneities reported by precedence researches. The observed amplitude growth rates show obvious correlation with the spatial distribution. It means that the fluctuation of growth rates is characterized by local heterogeneities. We suggest that regional relationships between growth rate and epicentral distances should be considered to improve the accuracy of the EEW.

IASPEI (Seismology, Geophysics)

S01eb - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-3623

Intelligence and statistics for rapid and robust earthquake detection, association and location

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For effective earthquake and tsunami early-warning it is crucial that key earthquake parameters are determined as rapidly and reliably as possible. This entails that initial estimates of earthquake parameters will be based on a minimal data set and are highly prone to error. These errors may be manageable and rapidly become small as more data is obtained. However, there may be large, persistent errors and bias in the earthquake parameters, indicating a much too high or low magnitude or hypocenter depth, a largely incorrect epicentre, or even a false event. The use of expert and machine intelligence and statistics based on past events can aid in identifying large, persistent errors and bias in earthquake parameters. At the INGV CAT* tsunami alert center, Early-est** is the module for rapid determination of the location, depth, magnitude, mechanism and tsunami potential of an earthquake. Early-est produces fully automatic results and their uncertainties in the shortest possible time using as few as 3 to 5 P onset observations. We present aspects of the intelligence and statistics used in Early-est to identify persistent errors and bias in the earthquake parameters. The R statistical computing and graphics language is used to exploit catalogs of past earthquake locations and phase data. We discuss indicators that are likely to be most efficient and reliable, such as measures of distance and azimuth distributions of detecting stations, the proportion of available stations that detect an event as a function of magnitude, and the goodness of fit of observed amplitudes to a theoretical attenuation law.

* CAT, “Centro di Allerta Tsunami”, part of the Italian, candidate Tsunami Service Provider ** Early-est (EArthquake Rapid Location sYstem with Estimation of Tsunamigenesis)

IASPEI (Seismology, Geophysics)

S01eb - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

IUGG-3925

Relationship between Mw and the arrival time of the peak high-frequency amplitude

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In the Earthquake Early Warning (EEW) of Japan Meteorological Agency (JMA) and Shinkansen (Japanese bullet train), M is determined using an amplitude measure and a pre-defined attenuation relation. The EEW systems underestimated M for the 2011 Tohoku earthquake (Mw 9.0) due to amplitude saturation. To solve this, Noda and Yamamoto (2014, AGU fall meeting) proposed a simple approach using the time difference (called “Top”) from the onset of body waves to the arrival time of the peak high-frequency acceleration amplitude to determine M. They showed that M estimated with this approach was accurate enough to be useful for EEW even in extremely large events (Mw > 8.3). Retrospective application of this algorithm to the 2011 Tohoku event reached its final value of M 9.0 145 seconds from the origin time. However, the theoretical relation between Mw and Top needs to be considered.

If Top is directly related to rupture duration, the slope of the relation between Mw and logTop should be 2 provided that the stress drop is scale invariant. We have measured Top by analyzing S-waves observed at K-NET stations (NIED, Japan) for 230 events with $4.0 \leq Mj \leq 9.0$ using a series of 1-octave band-pass filters between 0.125 Hz and 16 Hz. This resulted in 14,167 measurements of Top. Using projection pursuit regression, we find that the slope is 2 for the higher-frequency range (> 2 Hz). The picking error of the S-onset has a significant effect particularly for small Top due to the characteristic of the logarithm. The slope is somewhat smaller than 2 when the hypocentral distance is large (> 150km). This may be a consequence of the incompleteness of the dataset, or propagation effects. These results suggest that Top of the high-frequency (> 2 Hz) accelerogram has value in the context of EEW.

IASPEI (Seismology, Geophysics)

S01ep - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

S01ep-294

A P-wave based, on-site method for earthquake early warning

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A new strategy for a P-wave based, on-site earthquake early warning system has been developed and tested on Japanese strong motion data. The key elements are the real-time, continuous measurement of three peak amplitude parameters and their empirical combination to predict the ensuing peak ground velocity. The observed parameters are compared to threshold values and converted into a single, dimensionless variable. A local alert level is issued as soon as the empirical combination exceeds a given threshold. The performance of the method has been evaluated by applying the approach to the catalog of Japanese earthquake records and counting the relative percentage of successful, missed and false alarms. We show that the joint use of three peak amplitude parameters improves the performance of the system as compared to the use of a single parameter. The proposed methodology provides a more reliable prediction of the expected ground shaking and improves the robustness of a single-station, threshold-based earthquake early warning system.

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S01ep - S01e Seismological Observation and Interpretation: Real-Time Seismology and Early Warning

S01ep-295

Progress on development of an earthquake early warning system using low cost sensors

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Taiwan is one of the leading countries in development of earthquake early warning (EEW) systems. The Central Weather Bureau (CWB) is the major institute to develop an EEW system in Taiwan since 1993. The National Taiwan University (NTU) also started to develop an EEW system for research purpose using low cost accelerometers since 2010. A total of 506 stations were deployed and configured in the 2014. The NTU system could provide earthquake information about 15 seconds from an earthquake occurrence. Thus, this system may provide early warnings for cities located at the distance greater than 50 km from the epicenter. Additionally, the NTU system also has an onsite alert function that triggers a warning sound for the incoming P waves greater than certain threshold. It could provide two to three seconds lead time before the time of peak ground acceleration (PGA) for the regions close to epicenter. A detailed shaking map was produced within one or two minutes after the earthquake occurrence by the NTU system. The high shaking regions of the shaking map could indicate the locations of damage and casualties and helps to estimate damage. Earthquake rupture direction is potentially identified according to the detailed shaking map and strong motion records of the NTU system.

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New methodology for tsunami runup estimation based on finite fault models.

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In this work we propose a new strategy to estimate runup heights. This is a difficult task, because of the time it takes to construct a tsunami model using real time data from the source. It is possible to construct a database of potential seismic sources and their corresponding tsunami a priori. However, such models are generally based on uniform slip distributions and thus oversimplify our knowledge of the earthquake source. Instead, we can use finite fault models of earthquakes to give a more accurate prediction of the tsunami runup.

Here we show how to accurately predict tsunami runup from any seismic source model using a new analytical solution that was especially calculated for zones with a very well defined strike, e.g. Chile, Japan, Alaska, etc. The main idea of this work is to produce a tool for emergency response, trading off accuracy for quickness. Our solutions for three large earthquakes are promising. Here we compute models of the run-up for the 2010 Mw 8.8 Maule Earthquake, the 2011 Mw 9.0 Tohoku Earthquake, and the recent 2014 Mw 8.2 Iquique Earthquake. Our maximum run-up predictions are consistent with measurements made inland after each event, with a peak of 15 to 20 m for Maule, 40 m for Tohoku, and 2,1 m for the Iquique earthquake. Considering recent advances made in the analysis of real time GPS data and the ability to rapidly resolve the finiteness of a large earthquake close to existing GPS networks, it will be possible in the near future to perform these calculations within the first five minutes after the occurrence of any such event. Such calculations will thus provide more accurate runup information than is otherwise available from existing uniform-slip seismic source databases.

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"PRESTo" Early Warning Algorithm at Central and Eastern European Earthquake Research Network: Lessons from Configuring an High Density Seismic Network

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Since 2002, OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) in Italy, the Agencija Republike Slovenije za Okolje (ARSO) in Slovenia, and the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) in Austria are exchanging seismic data in real time. The data exchange is very effective for seismic events at the borders between Italy, Slovenia and Austria, where the poor coverage of individual national seismic networks precluded a precise earthquake location. In 2014, OGS, ARSO and ZAMG seismic networks participated in the creation of the Central and Eastern European Earthquake Research Network (CE^{3}RN).

In order to extend CE^{3}R Network monitoring towards earthquake early warning applications, at the end of 2013 OGS, ARSO and ZAMG teamed with the RISSC-Lab group at the Naples University Federico II in Italy. The collaboration focuses on testing the platform PRESTo (PRobabilistic and Evolutionary early warning SysTem) developed by RISSC-Lab on CE^{3}RN data. PRESTo is a stand-alone software that processes real-time data streams from a seismic network to promptly provide probabilistic and evolutionary location and magnitude estimates of detected earthquakes while they are occurring, as well as shaking prediction at the regional scale.

Since the beginning of 2014 PRESTo is running at CE^{3}RN, originally collecting and analyzing in real-time data streams from 20 stations. At the beginning of 2015 PRESTo@CE^{3}RN has been upgraded to add real-time data streams from broad band seismometers to the already configured accelerometers, thus more than doubling the total number of stations to the actual 43. This required accurate testing to define the best configuration of the system: we will illustrate here insight of the configuration with results in system performances.

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Characteristics of ocean bottom seismograph data during strong shaking and influence on magnitude estimation for earthquake early warning

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In Japan, large-scale In-line cable type ocean bottom seismographs (OBSs) are now under construction to make use of those data for real-time monitoring, and it is expected to utilize those systems for EEW. However, since OBSs are installed on soft sedimentary layer, the installation environment of OBSs may be different from that of land stations. Yamamoto et al. (2004) pointed out that one of Off-Kushiro OBS (JAMSTEC) was rotated about 5 degree by strong ground motion during the 2003 Tokachi-oki earthquake of Mjma8.0. The inclination of OBS causes baseline offset change in acceleration waveform on the gravitational acceleration component. Furthermore, it is also inferred that coupling of the OBS and the ocean floor becomes weak. Since the processing of the EEW is ongoing in real-time, it is difficult to detect abnormal data appropriately. In this study, we investigate the characteristics of OBS data during strong shaking at the Off-Kushiro OBSs. First, we estimate the amount of acceleration offset caused by rotation of the cable. The acceleration offset by slight inclination of OBS increases with input acceleration. And it is found that the acceleration offsets is larger on the horizontal component (Y', perpendicular to the cable line) than the other horizontal component (X', along the cable line). Second, we compare difference between S-wave H/V spectral ratio for strong ground motion and that for weak ground motion to investigate nonlinear response. We found that the S-wave H/V ratio for strong motion at OBS has typical features of nonlinear response, which is similar with land stations. Finally we discuss influence for EEW magnitude estimation. We will propose a new stable magnitude estimation method by using vertical component.

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Maximum likelihood earthquake location with multiple characteristics of P waves

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Recently, a robust location method for earthquake early warning (EEW) (Sheen, 2015), based on the maximum likelihood estimation (MLE), has been proposed. It has been shown that this method could reliably estimate an event location only with a few P wave arrivals, even when contaminated by an outlier. However, it still has poor resolution for the event outside the seismic network because a probability density function (PDF) for the MLE, generated from the residual between observed and predicted differential P wave travel times between two seismic stations, becomes ill-shaped especially at exterior along the azimuthal direction connecting two stations.

While most of the multi-station method or network method for EEW utilizes only P arrivals for estimating an earthquake location, the single station method utilizes various characteristics of P waves, such as back azimuth, incident angle, and initial slope, as well as arrival time. In this study, epicentral distance and back azimuth estimated from each single station are combined with P arrivals. The epicentral distance, estimated from the B-Delta method (Odaka et al., 2003) and the back azimuth from the principal direction of P wave are represented as PDFs and formulated to construct the likelihood function for the MLE. The improvement is demonstrated by the Monte Carlo experiment, which shows that the use of multiple characteristics of P waves greatly contributes to elevate the location accuracy of the events occurring outside the network.

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S01ep-300

The use of spectral content to improve earthquake early warning systems in Central Asia: Case study of Bishkek, Kyrgyzstan.

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Expansion of urban areas in Central Asia increases their exposure to seismic hazard, but at present no earthquake early warning (EEW) systems exist in the region. Such systems, successfully implemented in other regions, aim to provide warning of the order of tens of seconds about impending disasters, enabling the first rapid response steps to be taken. The feasibility of such systems for Bishkek, Kyrgyzstan, has been demonstrated. This study investigates how the use of the spectral content, instead of just ground motion thresholds, can be used to improve the performance of proposed regional warning systems. We find that using the spectral content of the first few seconds after the P-wave arrival can provide timely warning for events closer to the target city than was possible with the threshold systems. It is further shown that for events less than 60 km from the target, any regional system needs to be complemented with an on-site one to provide a comprehensive EEW system.

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S01ep-301

Site amplification factors of Japan area and their application to the real-time prediction of ground motion

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We aim to construct a new earthquake early warning system where we predict ground motion in real-time directly from observed waveforms, without estimating hypocenter and magnitude. In this framework, the data assimilation technique plays an important role. Original observed waveform, however, includes a site amplification which is peculiar to each station so that we have to correct the site amplification factors from observed waveforms before applying the data assimilation.

In this study, we estimated the site amplification factors of many stations which cover almost whole of Japan using spectral ratios of direct S-wave in adjacent two stations and inversion of the spectral ratios of many station pairs simultaneously. Next, we designed the digital filters which approximate the frequency characteristics of the site amplification factors. These filters satisfy the causality so that we can apply them in real-time.

Then, we tried to predict the seismic intensity on Japanese scale of a station from waveforms observed at adjacent stations with correction of site amplification factors. We compared two prediction methods: one was called frequency-dependent correction, using the filters described above, and the other was called scalar correction using a mean of differences of seismic intensity between two stations. Note that both methods can be applied in real-time. Mean root-mean-square of residuals of predicted seismic intensity was improved 5 % in frequency-dependent correction in the case that the distance between two stations are within 30 km. The precision of prediction was improved with decreasing the distance of two stations. This fact shows the importance of considering the frequency characteristics of site amplification factors in predicting a ground motion.

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S01ep-302

Near real-time seismic processing system for the Northern Caucasus region

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The Northern Caucasus is one of the most seismically active regions of the Russian Federation. At the moment, the system of seismological monitoring of the Northern Caucasus region includes 56 seismic stations. The system of automated data processing based on the SeisComP3 software platform was tested for Northern Caucasus network in 2012 – 2014.

Analysis of the level of background seismic noise was performed in order to correctly assess sensitivity of the network for regional earthquakes. Analysis of seismograms showed that only 5 stations installed in places that can be considered as quiet: noise level is close to the lower boundary of the Peterson's model. For 17 stations the noise level can be estimated as the average and for others it is high or very high.

Earthquake catalog including more than 600 earthquakes with magnitudes M_L in the range from 1.5 to 5.7 was generate during 2 year period of automatic processing. The catalog has been used to evaluate the performance of the monitoring system. Firstly the analysis of system response speed was done. It showed that first solution for the vast majority (89%) of earthquakes is obtained in the range from 2 to 5 minutes after their initiation. Furthermore, sensitivity of the monitoring system was assessed. The operating system in an automatic mode ensures the minimum representatively registered magnitude 2.5 in the central part of the Caucasian region and 3.0 - in its western and east parts.

At the moment, operations on the selection of optimal filters for signal detection with STA/LTA algorithm are underway. This will allow to increase the accuracy of evaluation of the hypocenters and to decrease the minimum representatively registered magnitude.

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S01ep-303

ALERTES-SC3: A prototype of an Earthquake Early Warning System based on SeisComP3.

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The Spanish ALERT-ES project was set up to study the feasibility of setting up an Earthquake Early Warning System to warn the potentially damaging earthquakes that can occur in the SW of Iberia peninsula, such as the 1755 Lisbon earthquake. As a part of this project, an EEWS prototype, called ALERTES system, based on SeisComP3 software, was developed for initial testing in real time for Ibero-Magrhebian region. In the frame of the currently ALERTES-RIM Spanish project (CGL2013-45724-C3-·R), this prototype is being updated taking into account the in-situ and the regional approaches. In this work the main features and characteristics and also the first results are shown.

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S01ep-304

Use of regional mB calibration functions to speed up magnitude computation

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Rapid quantification of earthquake size remains a challenge of real-time seismic monitoring. Significant progress has been made over the last decade, especially following the Indian Ocean tsunami of 2004, both by means of magnitudes (e.g., Hara, 2007; Lomax and Michelini, 2007; Bormann and Saul, 2008) as well as direct Mw measurement (e.g. Kanamori and Rivera, 2008).

The classical Gutenberg body-wave magnitude mB is computed from displacement amplitude (A) and period (T) and a calibration function Q, which is a function of focal depth z and epicentral distance delta: mB = log10(A/T)max + Q(delta,z). The original Q of Gutenberg and Richter (1956) is still widely in use. However, it is of poor quality at regional distances below 20 degrees, due to few regional measurements avalailable to G&R for its derivation in 1956. As an alternative to using displacent amplitudes, Bormann and Saul (2008) proposed the use of the peak P-wave velocity and substitute log10(A/T)max by log10(Vmax/2pi) to simplify mB determination. This has been accepted as IASPEI body-wave broadband magnitude standard mB_BB in order to complement the common short-period narrowband magnitude standard mb, which saturates much earlier.

From about 25 years of archived broadband data we derived a global Q for mB_BB. It can be used as a direct replacement of the G&R Q and allows reliable mB_BB computation including the distance range 5-20 degrees. By using mB_BB as proxy to estimate Mw (Bormann and Saul, 2008) and by covering the regional distances, good Mw estimates become possible within 5 minutes of origin time. This is crucial in regions where tsunami warning times are very short.

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IUGG-1473

Pacific Array

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Based on our recent results on broadband ocean bottom seismometry, we propose a next generation large-scale array experiment in the ocean. Recent advances in ocean bottom broadband seismometry (e.g., Suetsugu & Shiobara, 2014, Annual Review EPS), together with advances in the seismic analysis methodology, have now enabled us to resolve the regional 1-D structure of the entire lithosphere/asthenosphere system, including seismic anisotropy (both radial and azimuthal), with deployments of ~10-15 broadband ocean bottom seismometers (BBOBSs) (namely "ocean-bottom broadband dispersion survey"; Takeo et al., 2013, JGR; Kawakatsu et al., 2013, 2014, AGU; Takeo, 2014, Ph.D. Thesis; Takeo et al., 2014, JpGU). Having ~15 BBOBSs as an array unit for 2-year deployment, and repeating such deployments in a leap-frog way (an array of arrays) for a decade or so would enable us to cover a large portion of the Pacific basin. Such efforts, not only by giving regional constraints on the 1-D structure, but also by sharing waveform data for global scale waveform tomography, would drastically increase our knowledge of how plate tectonics works on this planet, as well as how it worked for the past 150 million years. International collaborations might be essential.

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S11a - S01g/S11 Seismological Observation and Interpretation: The Future of the Global Seismic Infrastructures, Forensic Seismology and CTBTO Data

IUGG-4244

International AlpArray science program calls for combined permanent and temporary seismic station array unprecedented in quantity and quality

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Recent methodological, technical and modeling advances in seismology provide the potential to illuminate 3D geometries and to assess local and regional structure, fabric, and flow patterns of the lithosphere-mantle system with unprecedented resolution and reliability if all kinds of seismic methods are brought to focus on same subsurface volume. In combination with the great wealth of readily available geologic information, of current numerical dynamic modelling capabilities and of new and unified gravity, strain and other geophysical maps for the region, such comprehensive seismic information will allow to tackle the problems and reach the scientific goals summarized in the AlpArray (AA) science plan.

To obtain the seismic data set of required quantity and quality, more than 600 approximately uniformly distributed BB stations must comprise a single seismic antennae operated for at least 1.5 years. This seismic station "AlpArray" may be established by combining the ≈300 permanent stations operated in the greater Alpine region by a dozen seismological observatories with a pool of temporary stations deployed and operated jointly by a group of institutions from at least seven countries. AlpArray seismic data will be collected, quality controlled, and made accessable following an agreed procedure guaranteeing highest standards and using the EIDA system.

In addition to the extensive AlpArray seismic network, a number of Complementary Experiments (AACE) will be conducted to focus on targeted problems. The first implemented AACE is called Eastern Alpine Seismic Investigation (EASI) targeting a number of open questions about the Eastern Alps. In this presentation we will dsiscuss the design of the experiments and report on first lessons learned with data management.

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IUGG-4904

The GEOFON program: past, current and future developments

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For more than two decades GEOFON [1] has operated both a global seismic network and a seismological data archive. The program started in 1992 evolving in synergy with the seismological community with a clear commitment towards open data policy as well as fostering new standards in seismology. The development and dissemination of the SeedLink protocol at the end of the 1990s fostering real-time networking of networks and data centers, the ArcLink protocol for networking data archives in the early 2000s and the SeisComP3 [2] software development triggered right after the 2004 Indian Ocean tsunami for near-real-time earthquake monitoring were major milestones.
The continued extension of the global seismic network, the ingestion of growing amounts of data into the archive and the operation of a global monitoring system [3], which is based on SeisComP3 and focuses on providing rapid location, magnitude and moment tensor information for large earthquakes worldwide, has positioned GEOFON as one of the global reference scientific infrastructures in seismology today.
Through its strong involvement in European infrastructural projects and by engaging in worldwide cooperation, GEOFON will continue to extend the provision of high quality data and related products. Only our continued clear commitment to open access and transparent policies will allow us to reduce to the minimum barriers between network operators, data centre operations and data users.
This presentation will describe the GEOFON program since the early nineties with particular emphasis on the ongoing activities and future perspectives.

[1] http://geofon.gfz-potsdam.de/
[2] http://www.seiscomp3.org/
[3] http://geofon.gfz-potsdam.de/eqinfo/

IASPEI (Seismology, Geophysics)

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IUGG-5143

The Brazilian seismic network - RSBR

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During the last few years a great effort has been done to install the new permanent Brazilian Seismographic Network (RSBR, www.rsbr.gov.br). Four different institutions are involved, the University of São Paulo (USP), the University of Brasília (UnB), the National Observatory (ON) and the Rio Grande do Norte Federal University (UFRN), each one being in charge of a number of stations. Today the network includes 80 broadband stations operating across different tectonic provinces and regions in Brazil, most of them with real time transmission through either 3G or satellite. Other institutions (UNESP, UFMS, and IPT) also contribute with additional stations or logistical support. RSBR has been funded by Petrobras Geotectonic Program.

Each of the four institutions uses Seiscomp3 to receive, analyze and archive data. A central archiving center is located in ON and data are accessible using the ArcLink protocol and/or Federated web-services. The data/services distribution topology is based on technology and concepts adopted by the EIDA network in Europe, making it as compatible as possible with EIDA. The stations are also registered at IRIS. Information about the stations and data availability can be seen at : http://www.rsbr.gov.br. At present, realtime data from some stations are shared with the national networks of Bolivia, Chile as well as GFZ-Potsdam.

The main purpose of the RSBR is to monitor the seismicity in Brazil, and publish a national seismic catalogue. We are now in the process of tailoring the communication system between the institutions in order to exchange parametric data in an efficient way. The high-quality continuous data will also support researchers to carry out new regional projects with temporary stations.

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IUGG-5160

NIED observation networks for earthquakes and tsunamis

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After the Kobe earthquake, NIED has operated K-NET and KiK-net (Strong Motion Seismograph Network), Hi-net (High Sensitivity Seismograph Network), and F-net (Broadband Seismograph Network) since 1996 for uniform coverage of national scale. These open high-quality data contributed to discover new geophysical findings of low-frequency tremors, extreme ground motions as well as in-depth imaging of the Earth. After the 2011 Tohoku earthquake, the Japanese government decided to construct a new ocean bottom observation network off the Tohoku coast considering the reference fact that non-plenty of data on the offshore source region during the megathrust event. NIED is constructing S-net (Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench) that consists of about 150 ocean bottom observation stations linked by fiber optic cables with about 5,700 km in total length, and covers wide area of the offshore Kanto, Tohoku, and Hokkaido. Each station is equipped with a series of geophysical sensors including strong motion accelerometers and pressure gauges. Data from the network will be utilized for earthquake and tsunami early warning and are expected to gain the extra lead time up to 30 sec and 20 min respectively for ground motions and tsunamis. Advanced research is developed for prompt tsunami early warning directly using the S-net data of pressure gauges observed right above the source region. S-net, as one of frontier networks, has a great potential to contribute further scientific findings.

IASPEI (Seismology, Geophysics)

S11a - S01g/S11 Seismological Observation and Interpretation: The Future of the Global Seismic Infrastructures, Forensic Seismology and CTBTO Data

IUGG-5521

Seismic networks and earthquake monitoring in Europe in the digital era: ORFEUS and the contribution of Torild van Eck

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We review the last 30 years of development of seismological networks in Europe in the digital era, and the contribution of ORFEUS to coordinate and integrate national and regional broadband networks. We highlight the contributions of Torild van Eck, who was the Secretary General of ORFEUS since 1997, and was a driving force in establishing best practice in seismic networks, coordinating the disperse monitoring community, providing open access to European seismic data and integrating Europe in the global FDSN coverage. Torild passed away in November 2014.

IASPEI (Seismology, Geophysics)

S11b - S01g/S11 Seismological Observation and Interpretation: The Future of the Global Seismic Infrastructures, Forensic Seismology and CTBTO Data

IUGG-2455

EPOS-Seismology: Integrating European Seismological Infrastructures

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With the successful completion of the Preparatory Phase project for the European Plate Observing System (EPOS), and in preparation for the EPOS Implementation Phase, the seismological community in Europe is continuing the integration and further development of European seismological infrastructures in the EPOS framework as the Thematic Core Service EPOS-Seismology.

The main goal of this endeavor is to strengthen our ability as a community to address current and future scientific challenges in the wider field of seismology, from basic understanding of Earth's structure and dynamics to the topics of geohazards and georesources and their societal impact. EPOS-Seismology is building on the existing European infrastructures in the domains of seismological waveform data (ORFEUS), earthquake parameters and seismological products (EMSC), and earthquake hazard (EFEHR), and continues the development of computational seismology services following the VERCE project. EPOS-Seismology aims at harmonized data, products and services throughout the whole utilization cycle (from raw waveform data and station information via event parameters, modeling, to seismic hazard and geotechnical engineering) that serve to increase interoperability, strengthen the interconnection between permanent (regional scale / national) seismological networks and dedicated multi-disciplinary observation infrastructures on active structures (volcanoes, faults), and maximize synergies across the different areas of seismology as well as with other relevant solid earth and IT science fields.

In this presentation we discuss the current roadmap for the organizational and technical developments in EPOS-Seismology and its connections to relevant infrastructures in other regions and on global scale.

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IUGG-2914

Detection capability estimation for the IFE14 seismic aftershock monitoring network

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The Seismic Aftershock Monitoring System (SAMS) is an important tool used during the initial period of an On-site Inspection (OSI) to narrow down the search area and identify the location of a possible underground nuclear explosion. A network of tripartite mini-arrays and single three-component seismic stations can be deployed during an OSI to detect and localize small aftershocks in the vicinity of a possible explosion.

During the Integrated Field Exercise (IFE14) in Jordan a trade-off between fast station deployment, precise site analysis and practicability from local conditions was made. A first rough site characterization was undertaken with information about geology, local facilities and infrastructure e.g. roads to select suitable sites and improve the network detection capability. Significant variations in topography of the inspection area in the mountainous Dead Sea Area of Jordan led to considerable limitations concerning the network design.

A comprehensive and analytical method to estimate the SAMS network detection capability will be presented which is based on noise measurements from SAMS stations. Results from this analysis would enable inspectors to adapt the network configuration to the needs by densifying the network or relocating stations. Additionally this systematic quality control enables inspectors to identify system failures and manipulation at the seismic stations.

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IUGG-3078

The MUSTANG data quality analysis system: Finding meaning in the metrics

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The IRIS DMC has derived more than two terabytes of statistical information that reflect different aspects of quality of the seismic data holdings at IRIS. MUSTANG is the name of the automated system at IRIS devoted to quality assurance of most data held at IRIS. This system calculates over 40 metrics related to data quality and makes the metrics openly available through web services. Its database is rapidly growing as it processes our archived and incoming datasets. With these metrics we can begin to put pieces of the data signal puzzle together to form inferences on the health of recording instrumentation, metadata validity, and the completeness and correctness of the data.

This presentation will describe how DMC analysts use MUSTANG to quickly find patterns of abnormal behavior in seismic data and how certain emergent characteristics in the metrics can point to issues that require software or hardware intervention to improve the data quality. The system is designed to easily add new metrics to identify other characteristics of the data that affect data usability. Various applications can be developed to automate data characterization, track data quality changes, and produce succinct reports for operators and stakeholders regarding the reliability of the data and instrumentation. IRIS views this as a value added service for networks that rely upon the IRIS DMC for management and distribution of their time series data.

Ultimately we hope to use MUSTANG metrics as key information that would allow researchers to specify data quality attributes as part of the request process in the Research Ready Data Sets (RRDS) effort that will begin development in 2016.

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IUGG-3717

An evaluation of claims on the merits of smart-phone sensors, for nuclear explosion monitoring

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In recent years it has been claimed that widespread use of smart phones, equipped with inertial sensors of ground motion, offer new opportunities to detect the seismic signals from underground nuclear explosions; and that such a capability can contribute to the work of monitoring for compliance with nuclear test ban treaties.

In general these opportunities are associated with two goals. First, to acquire data with the potential to reveal the occurrence of banned activities that would otherwise go undetected by conventional sparse networks. Second, to involve the general public in the practical work of treaty verification ("crowd-sourcing") rather than leaving this burden wholly with specialized experts.

In the context of nuclear explosion monitoring it is important to examine the technological foundation and data analysis underlying such claims, given that smart phone sensors have intrinsic merits and limitations. Cheap sensors clearly have merits in some types of seismic monitoring.

This presentation will report the preliminary results of a comparison between recordings of ground motion made by Observatory-quality sensors of ground motion and recording systems, for known signals of different types (with amplitudes large and small and in different frequency bands), and the recordings made at the same time and on the same pier by smart-phone sensors.

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IUGG-4519

Could the International Monitoring System infrasound stations support a global network of small aperture seismic arrays?

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The International Monitoring System (IMS) infrasound arrays have up to 15 sites with apertures up to 3 km. They are distributed remarkably uniformly over the globe, providing excellent coverage of South America, Africa, and Antarctica. Therefore, many infrasound arrays are in regions thousands of kilometers from the closest seismic array. Existing 3-component seismic stations, co-located with infrasound arrays, show how typical seismic signals look at these locations. We estimate a theoretical array response assuming a seismometer at each infrasound sensor, although the true performance would depend upon both signal-to-noise ratio and coherence. These properties can however only be determined experimentally and borehole deployments may be needed to record seismic data of sufficient quality. We demonstrate, from a purely geometrical perspective, that essentially all IMS infrasound array configurations would provide seismic arrays with acceptable slowness resolution. Such arrays in many regions would likely enhance significantly the seismic monitoring capability in parts of the world where only 3-component stations are currently available. Co-locating seismic and infrasound sensors would mitigate the development and operational costs due to shared infrastructure, and hosting countries might find such added capabilities valuable from a national perspective. The seismic data may allow far more information to be gleaned from the infrasound data.

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IUGG-5182

Portable Seismic Array Observation in China mainland

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In order to study the deep structure and geodynamic evolution of eastern Asia, we have established a Seismic Array Laboratory (SAL) and performed 22 portable seismic array observations in China mainland and abroad since 2000. Up to now, SAL has 420 sets of broadband seismographs, and 15 scientific research groups from China have used these seismographs and deployed more than 1200 portable seismic stations. In most case, the arrays are linear ones with a spatial interval of 10-15 km between two adjacent stations and each station has operated 12-18 months.

The portable seismic arrays were mainly distributed in North and Southwest China, Tibet and Tethys orogenic belts such as Alps area from French to Italy and the Zagros Fold in Iran. Seismologists who used instruments have collected and analysed a huge raw seismic data, and have made many important achievements, such as the detail interior structure of North China Craton, the crustal and mantle structure beneath the Tibet and Iranian Plateaus.

The seismographs in SAL are used for portable seismic observations and are opened to all seismologists who aim at seismic research. Users who implement seismic observations with the seismographs in IGGCAS have three years priority to use the corresponding seismic data after field operation. Then, those data should be released by the SAL. Parts of the data have been open to public through the website http://www.seislab.cn/data, and currently, more than 12000 records have been downloaded from this website.

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Another view of the history of the Cepstrum

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Since this conference, and this paper, come at the twilight of my career, I thought that it would be appropriate to share my views on a subject very dear to my heart and to my long career.

In 2004 'From Frequency to Quefrency: A History of the Cepstrum' was published in the IEEE Signal Processing magazine. There is no question that the authors, Alan V. Oppenheim and Ronald W. Schafer, were early pioneers in this research, and this publication documents their involvement quite nicely. Researchers Childers, et al., renamed the original “Cepstrum” to the “Power Cepstrum” to avoid confusion with the principal topic of their research, that being the “Complex Cepstrum.” The term “Power Cepstrum” has become widely used in the literature since that time. The Childers team, including Dr. Kemerait, published a summary of its work, as of that date, in the IEEE Proceedings of October 1977 and titled the article “The Cepstrum: A Guide to Processing.”

In the forty-three subsequent years, Dr. Kemerait has continued to perform research utilizing cepstral techniques on many diverse problems; however, his primary research has been on the depth of an underground or underwater event.

He has applied these techniques to biomedical data, EEG, EKG, and Visual-evoked responses as well as on hydroacoustic data that can determine the “bubble pulse” frequency and the depths of the explosion and the water column. He has used it extensively in ground penetrating radar, speech, machine diagnostics, and, throughout these years, seismic data. This paper emphasizes his research on seismic data with emphasis on the Complex Cepstrum.

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Seismic and acoustic signals associated with flight of Carrier rockets launched from Baykonyur cosmodrome on the records of Kazakhstan stations

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Tens of rockets are launched each year from Baykonur cosmodrome located in Central Kazakhstan. The rockets flight routes are above several Kazakhstan regions. The Institute of Geophysical Researches conducts seismic and acoustic monitoring of events of different nature round-the-clock. The records of Kazakhstan seismic stations and infrasound arrays show phenomena related to rockets launch, rocket stage separation, PLF jettison, descend of landing sections, and accidents. The catalogue of events associated with rockets flight was compiled; peculiarities of the wave pattern, kinematic and dynamic parameters of these events were investigated.

The signals from accidents of Dnepr rocket of July 26, 2006 and Proton rocket of September 5, 2007 and of July 2, 2013 were studied in details. Correct interpretation of non-traditional seismic sources and its exclusion from seismic bulletins allows improving of catalogues quality, in case of accident this information helps to estimate the event parameters and to start recovery procedures in proper time

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Identification of natural phenomena (nontectonic) records by Kazakhstan seismic stations

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At the present time, numerous seismic stations located on the territory of Central Asia send data to Kazakhstan National Data Center, Almaty, in real time. The KNDC monitors seismic events of different nature, first of all these are earthquakes and mining blasts. And, usually, there is no much attention to other signals appeared in seismograms. These are not identified and, often, are considered as noise. However, there are events that erroneously are processed as tectonic earthquakes, but are not the earthquakes.

Recently, KNDC has managed to investigate the wave pattern of some classes of natural (nontectonic) phenomena and identify them accurately. The records of such natural phenomena as avalanches, mud flows and landslides, thunderstorms were received at the region of seismic stations. The signals related to Chelyabinsk meteorite were recorded; these signals allowed locating point of the Earth impact of powerful sound wave and determining seismic energy parameters of this event. Another class of events is connected with processes in ice and glaciers. Large amount of the recorded signals showed ice breakup in lakes. Thousands of small events previously entered into the earthquake catalogues are currently identified as ice and glacial earthquakes.

The following unique criteria for identification of non-seismic natural phenomena using records of standard seismic stations were determined for a definite class of signals, these are: difference of spectrums, building-up period of maximum, period of peak amplitude, record duration, availability of additional infrasound signal.

Correct interpretation of non-traditional seismic sources and its exclusion from seismic bulletins allows improving of catalogues quality and more precise evaluation of seismic mode parameters.

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Optimization of a waveform-fetching algorithm based on station detection capability thresholds

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With the development of modern seismic instruments and the installation of new seismic stations, the availability of data volumes has increased dramatically. However, the routine monitoring of the station quality characteristics alone (e.g., signal-to-noise ratio), is not always sufficient to provide information regarding the station's capability to detect seismic events, since focal depth variations, directivity and azimuthal coverage effects are usually neglected. Moreover, given a particular event (magnitude, location, depth) the question arises over which stations are more likely to record this event. We try to overcome these limitations, by developing new probabilistic seismic station selection schemes based on (i) station, and (ii) event capability detection maps. The maps are built using m_{b1} body-wave magnitude detection threshold estimates based on the International Data Centre - Reviewed Event Bulletin (IDC-REB). Robust detection capability thresholds are calculated for 5,703 stations of the International Seismograph Station Registry (IR). The detection threshold estimates are then grouped into maps with respect to (i) station locations, and (ii) event locations. To assess these schemes, we compare the results of a waveform-fetching algorithm by using the two selection schemes mentioned above. We find no significant differences for events with $m_{b1} < 4.2$, whereas larger events ($4.2 \leq m_{b1} \leq 4.8$) show that the algorithm based on the event detection map systematically filters out stations at long epicentral distances that are less likely to record seismic signal, and fills in gaps due to lack of detection threshold estimates up to 40° in epicentral distance.

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BJT and its development

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BJT has been a CTBTO/IMS auxiliary station for near 20 years, and the data has been contributed to China National Seismic Network and US Global Seismographic Network.

BJT as a seismic station took down the first seismograph of China in 1957.At present, in the 80m-depth cave which was built in 1950s, there deployed 3 seismographs, a gravity meter, a tilt meter and 2 strain meters, while 4 magnetometers, a borehole water-level meter and 2 thermometers with different depth were installed in the yard of BJT.

From 2000s, BJT became the Beijing National Earth Observatory (NEOBJI), which was hornoured as one of the 14 National Field Stations for Geoscience by the Ministry of Science and Technology of China. Besides the earthquake and geophysics related monitoring at BJT, a laboratory focused on rock physics and an equipment center to control quality for seismometers and accelerators was built up around 2007. Nowadays, waveform data from the stations located in the capital area, geomagnetism data in mainland China and real-time mobile seismological data can be shared at BJT. It could be wished that BJT will contribute more than before to CTBTO task.

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Announced test as a new challenge to the international monitoring system (IMS): a game theoretic perspective

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Since the 1990s, announced tests have put forward new questions for the international monitoring system (IMS) which was previously designed for the detection, screening, identification, discrimination, and characterization of clandestine tests. One of the questions arose is whether announced tests are a trend in the ‘test-monitoring game’, or they are just occasional events. I try to use game theory to demonstrate that, with the development of the international monitoring system, announced test is a rational strategic choice of the countries trying to ‘enter the nuclear weapon club’, forming a new challenge to the international monitoring system. Having successfully explained the ‘nuclear threaten equilibrium’ and the strategic choices of the Korean peninsula nuclear crisis, which have all become the textbook examples, game theory deals with the competition among different rational agents, discussing the equilibrium of the strategies of different players. With cautions in mind about the limitation of such a conceptual discussion, game theory may provide some insights into the design of the future international monitoring system. Also importantly, the ‘international game’ of nuclear test versus monitoring, with rich experiences and lessons during its long history, may potentially be able to contribute to the study and education of game theory.

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Improving CTBTO monitoring capabilities: the Italian proposal for a CNF

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The Centro di Ricerche Sismologiche (CRS, Seismological Research Center) in Udine (Italy) of the OGS (Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), the Italian National Institute for Oceanography and Experimental Geophysics, after the M=6.4 earthquake occurred in 1976 in the Friuli-Venezia Giulia region, started to operate the Northeastern Italy Seismic Network: it currently consists of 18 very sensitive broad band and 20 simpler short period seismic stations, all telemetered to and acquired in real time at the OGS-CRS data center. OGS is formally part of the Central and Eastern European Earthquake Research Network CE^3RN (http://www.CE3RN.eu/). Real time data exchange agreements in place with CE^3RN and other Italian and Swiss seismological institutes lead to a total number of about 100 seismic stations acquired in real time by the CRS, which makes the OGS the reference institute for seismic monitoring of Northeastern Italy.

To further support CTBTO activities, OGS proposes with the support of the Italian CTBTO National Authority one of its stations of the Northeast Italy Seismic Network as a Cooperating National Facility (CNF) to the CTBTO. A description of the Cludinico (CLUD) station proposed as CNF, together with results of CTBTO monitoring improvements simulations will be illustrated.

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Estimation of the TNT equivalent charge for large surface experimental and accidental explosions based on seismo-acoustic observations

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Traditional forensic seismology techniques utilize seismic and acoustic waves, propagating through the Earth and the atmosphere accordingly, to study distant explosions, including accidental blasts, bomb attacks and nuclear tests, and evaluate the source signatures. Accurate and reliable TNT equivalent charge weight is an important parameter for investigation of technological features of the explosion. Usually this value is estimated from measurements of dynamic parameters of observed seismic and acoustic (airblast) waves: peak amplitude, dominant period, duration and impulse of the positive airblast phase. These measurements require expensive recording equipment, calibrated seismometers or high-pressure sensors, well-protected from the blast impact.

A new estimation technique is presented based on measuring a new parameter of airblast waves: the time delay between the Secondary and Primary Shock arrivals. The delay was found depending on the charge weight, distance and type of explosives, and an appropriate relation was developed. This differential parameter is a reliable and stable air-blast feature, easily measured from records of any low-cost acoustic (microphone) or seismic (seismometer, accelerometer) non-calibrated sensor or even from home video-camera, placed at remote locations where protection is not necessary. The delay depends on the explosives velocity of detonation, thus serving in some cases as an indicator of the blast nature and characteristics. The new technique features make it especially relevant and useful for investigation of blast accidents and bomb attacks.

The presented analysis is based on data obtained for large surface explosions, designed and conducted by the Geophysical Institute of Israel at Sayarim Military Range in 2009 and 2011.

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On the possibility of imminent regional seismic activity forecasting using geomagnetic monitoring and Sun- Moon tide code data

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In it presented an approach for the imminent regional seismic activity forecasting by using geomagnetic data and Earth tide data. The time periods of seismic activity is the time periods of the Sun – Moon extreme of diurnal average value of module of vector Tide (North, East, Down). For analyzing the geomagnetic data we use standard deviation of their diurnal components F (North, East, Down), for calculation the time variance GeomagSignal of geomagnetic field. To avoide the Sun storms influence we use data for daily A-indexes values, published by NOAA. The precursor signal for estimation of the incoming regional seismic activity is a simple function of today and yesterday GeomagSignal and A- indexes values.

The reliability of geomagnetic “When, where (regional)” precursor is demonstrated by using statistical analysis of day difference between the times of “predicted” and occurred earthquakes in the frame work of the natural hypothesis that the “predicted” earthquake is this one which energy surface density in the monitoring point is bigger than energy densities of all other occurred in the same period and region earthquakes.

The approach’s reliability was tested using the INTERMAGNET stations data located in Bulgaria Panagurishte, PAG (Jan 1, 2008- Jan 29, 2014), Romania, Surlari, SUA (Jan 1, 2008- Jan 27, 2014), Serbia, Grocka, GCK (Jan 1, 2008- Jan 27, 2014), Italy, L’Aquila, AQU (Jan 1, 2008- May 30, 2013) and Skopje, SKO (2007-2014) in the time EU IRSES BlackSeaHazNet (2011-2014) project.

Shortly are discussed the steps for solving the “when, where and how” earthquake prediction problem.

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ADDOSS: Autonomously Deployable Deep-ocean Seismic System - Communications Gateway for Ocean Observatories

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We describe an autonomously deployable, communications gateway designed to provide long-term and near real-time data from ocean observatories. The key features of this new system are its abilities to telemeter sensor data from the seafloor to shore without cables or moorings, and to be deployed without a ship, thereby greatly reducing life-cycle costs.

The free-floating gateway uses a Liquid Robotics wave glider comprising a surfboard-sized float towed by a tethered, submerged glider, which converts wave motion into thrust. For navigation, the wave glider is equipped with a small computer, a GPS receiver, a rudder, solar panels and batteries, and an Iridium satellite modem. Acoustic communications connect the subsea instruments and the surface gateway while communications between the gateway and land are provided by the Iridium satellite constellation. Wave gliders have demonstrated trans-oceanic range and long-term station keeping capabilities.

A shallow tow body houses a WHOI acoustic micro modem and a Benthos low frequency, directional transducer. A matching modem and transducer are mounted on the ocean bottom package.

Tests of the surface gateway in 4350 m of water demonstrated an acoustic efficiency of approximately 396 bits/J. It has the ability to send 4 channels of compressed, 1 sample per second data from the ocean bottom to the gateway with an average power draw of approximately 0.15 W and a latency of less than 3 minutes.
We present results from several short-term OBS tests off-shore La Jolla, at water depths of 1000 and nearly 4000 m.
Ultimately, the package will be outfitted for two-year operations. Such data from presently unobserved ocean sites are critical for scientific research ranging from Earth structure to monitoring earthquakes and tsunami.

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Seismic Response Controlling of Structures with a New Semi Base Isolation Devices

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The numbers of devices which are used to control of seismic in structures have been developed during past decades and base isolation design is a new technology on seismic control of structures, the important reasons for the delay of use new technology of base isolation system almost referred to the mentality of the builder (especially in underdeveloped country) and high cost of the new technology, This study is an attempt to introduce an effective way to protecting of structures against grand motions by new method (semi base isolation system). In the new way structures isn't completely decouple of bases and it changed natural frequency of structures due earthquake by changing horizontal stiffness.

The proposed semi base isolation (SBI) system were applied to a one story frame and compared with end fixed frame and the time history analysis was conducted on record of Kobe earthquake (1995), San Fernando (1971) and Santa Barbara (1978), by used finite element software (ABAQUS 6-10-1). The analysis results can shows that the efficiency reduced the floor acceleration and displacement and velocity. This study shows that (SBI) system has great potential in future application of seismic isolation technology.

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Earthquake monitoring in Greenland - benefits of the GLISN infrastructure

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With the purpose of detecting, locating, and characterizing glacial earthquakes and other cryo-seismic phenomena, and contribute to our understanding of Ice Sheet dynamics the Greenland Ice Sheet Monitoring Network (GLISN) project was launched in 2009. As a seismic infrastructure GLISN has from day one produced high quality, real time and free broad band data from existing and new locations in and around Greenland. As a spinoff from the GLISN project the earthquake monitoring in Greenland have been improved significantly, we here report the improvements and progress of the earthquake monitoring, to illustrate the value and benefits of large scale seismic infrastructures and of free research data. GLISN is a corporation of research institutions from 11 countries (GLISN, http://glisn.info).

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Development of web application system for waveform data observed by real-time seafloor seismic network

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Mega-thrust earthquakes are anticipated to occur in the Nankai Trough in southwest Japan. In the source areas, we installed real-time seafloor seismic network, DONET (Dense Ocean-floor Network System for Earthquake and Tsunamis), in order to monitor seismicity, crustal deformations, and tsunamis. DONET system consists of 20 stations, which is composed of six kinds of sensors; strong motion and broadband seismometers, quartz and differential pressure gauges, hydrophone, and thermometer. The stations are densely distributed with an average spatial interval of 15-20 km and cover near coastal areas to the trench axis. We have developed two application using web browser; monitoring waveform and download seismic data, respectively. Monitoring system can view the strong motion and pressure gauge in real-time to promptly identify crustal deformation and tsunami for the use of disaster prevention officer of local government. After the 2011 Tohoku Earthquake (Mw9.0), some local government, especially located along Nankai trough, need to organize regional disaster prevention plan based on the disaster management plan of national government. Obtaining and storing knowledge about earthquake and tsunami is essential to provide prevention plan, and getting information immediately is important for executing their scheme. Another system allows researchers to download strong motion (EH type) and broadband (BH type) seismograph data as SEED file. The seismic event data are produced referring to event catalogues from USGS and JMA (Japan Meteorological Agency), Magnitude greater than 6 for far-filed and greater than 4 for local seismicity, respectively.These applications provide seismological information through the web browsing technology and allow users to view and use DONET data easily.

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The GEOSCOPE seismic network

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The GEOSCOPE observatory provides 33 years of continuous broadband data to the scientific community. The 31 GEOSCOPE stations are installed in 19 countries, across all continents and on islands throughout the oceans. They are equipped with three component very broadband seismometers (STS1 or STS2) and 24 or 26 bit digitizers (Q330HR). Seismometers are installed with warpless base plates, which decrease long period noise on horizontal components by up to 15dB. In most stations, a pressure gauge and a thermometer are also installed. 27 stations send data in real or near real time to the GEOSCOPE Data Center and are automatically transmitted to other data centers, including tsunami warning centers. We plan to install two new stations, in Saint Pierre and Miquelon Island (off the East coast of Canada) and in Rapa island (South Pacific Ocean).

Continuous data from all stations are collected in real time or with a delay by the IPGP Data Center in Paris where they are validated, archived and made available to the international scientific community through different interfaces (see details on http://geoscope.ipgp.fr). The data are duplicated and made accessible at the IRIS-DMC data center; in 2015, they will also be duplicated and made accessible through the french national data center RESIF.

We perform scientific data validation by analyzing the spectral characteristics and the noise level of the continuous data every 24 hours. We also validate data by comparing real and synthetic body-wave waveforms using the SCARDEC method (Vallée et al., 2011). Information on earthquake characteristics, on the GEOSCOPE data available for each event and on the waveform fit for each channel is available through the GEOSCOPE web portal.

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Seismic event identification by spectral pattern recognition and combination of array and network localization during IFE14.

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Due to the location of the Integrated Field Exercise (IFE14) inspection area in Jordan on the Dead Sea Rift, an abundance

of natural seismic events and quarry explosions had to be ruled out as possible aftershocks

from an underground nuclear explosion for the on-site insection (OSI) seismic aftershock monitoring system

(SAMS). The extreme topography and restrictions led to a reduced number in deployed miniarrays.

Nevertheless, SAMS successfully detected all scenario relevant events. This study

shows the current SAMS manual detection and localization techniques and how they can be

extended with automatic routines. The detection of local events with low signal-to-noise ratios at

very few stations (<3) with a duration of few seconds can't be realized with detectors based

solely on coincidences of amplitude variances (e.g. STA/LTA) or changes in the statistic

distribution of ground velocities. An abundance of local noise sources triggers false detections

continuously. The use of matched filters is limited due to the low-SNR and short epicentral

distances. Instead a pattern recognition based on robust noise adapted spectrograms is used.

The automatic localization is done through a combination of beam-forming, fk-analysis, phasepicking

and a weighted 3D grid-search which takes the certainty of each information and the

topography of the area into account.

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The IRIS Federator: Accessing seismological data across data centers

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In 2013 the International Federation of Digital Seismograph Networks (FDSN) approved a specification for web service interfaces for accessing seismological station metadata, time series and event parameters[1]. Since then, a number of seismological data centers have implemented FDSN service interfaces[2], with more implementations in development. Leveraging this standardization, the IRIS Data Management Center (DMC) has developed capabilities to make the discovery and access of data across FDSN data centers easier. Collectively known as the IRIS Federator, the main components are a catalog of channel metadata holdings across FDSN data centers and a web service interface for searching the catalog. The catalog service interface has been designed to support client-side federated data access by accepting requests exactly as they would be submitted to FDSN-standardized fdsnws-dataselect or fdsnws-station service interfaces and returning results that are formatted for submission to those same interfaces. Alternatively, the results may be returned in a simple, channel-level text format for general channel discovery purposes. By default, the interface will remove any duplication of time series channels between centers according to a set of business rules. Optionally, a user may request results with all duplicate channels included. Utilizing this capability, client-side federation has been added to some of the DMC's data access clients. We expect the IRIS Federator will evolve in order to satisfy more multi-data center discovery needs and we expect developments of the Federator to continue as discussions with other data centers take place.

1. http://www.fdsn.org/webservices/
2. http://service.iris.edu/irisws/fedcatalog/1/

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Characteristics of regional seismic waves from large explosive events including Korean nuclear explosions

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Three North Korean underground nuclear explosion (UNE) tests were conducted in 2006, 2009 and 2013. Discrimination of explosions from natural earthquakes is important in monitoring the seismic activity in the Korean Peninsula. The UNEs were well recorded by dense regional seismic networks in South Korea. The UNEs provide unique regional seismic waveforms with high signal-to-noise ratios. However, the continental crust in the Korean Peninsula changes abruptly into a transitional structure between continental and oceanic crusts across the eastern coast. The complex geological and tectonic structures around the Korean Peninsula cause significant variations in regional waveforms. Outstanding question is whether conventional discrimination techniques can be applicable for explosions including the North Korean UNEs. P/S amplitude ratios are widely used for seismic discrimination. To understand the regional shear-energy composition, we analyze the frequency contents of waveforms. The result shows that the UNEs are successfully discriminated from earthquakes in the Korean Peninsula. We also analyze the explosive events not UNEs from North Korean to test the applicability of the discrimination technique. The result of high frequency Pn/Sn regional discrimination in the explosions show that as magnitude of event is smaller, available distance of discrimination is decreased particularly in high frequency range. The poor signal to noise ratio of Pn phase in the explosions, and inefficient propagation of Sn phase in the Western part of the peninsula frustrate Pn/Sn discriminant, while the UNEs show good performance using both discriminants because of propagation path effects in the eastern part of the peninsula.

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The current status of the global seismographic network (GSN)

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The Global Seismographic Network (GSN) is a state-of-the-art, globally distributed network of 150+ permanent seismological and geophysical sensors, and is a cooperative partnership between the Incorporated Research Institutions for Seismology (IRIS) and the U.S. Geological Survey (USGS). The GSN coordinates closely with other international seismic networks through the International Federation of Digital Seismograph Networks (FDSN). In collaboration with the USGS National Earthquake Information Center (NEIC), the network provides a community resource for earthquake monitoring, research and education. The GSN streams critical data to the National Oceanic and Atmospheric Administration (NOAA) Tsunami Warning Centers for rapid response to large, tsunamigenic earthquakes.

Recently the GSN upgraded all stations to the next generation DAS and, starting in 2015, will develop the Very Broad Band Borehole Seismometer (VBBBS) to replace obsolete sensors. In parallel, the GSN is implementing a data quality assurance system to ensure that quality of the data from the GSN is as high as possible and to communicate the level of data quality in a consistent manner both within the network operational groups and to the GSN data user community.

The availability of a relatively uniform, high quality set of seismic data has enabled construction of large, detailed catalogs of earthquake locations and magnitudes. Observations from the GSN have improved imaging of the Earth’s interior and supported better understanding of earthquake processes. Major challenges for the GSN include managing the aging station infrastructure, continuing the quality assurance effort and deploying and operating high quality stations in the deep ocean basins.

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A web service standard for seismological data

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The International Federation of Digital Seismograph Networks (FDSN)[1] has published a specification[2] defining web service interfaces for accessing seismological time series data, related metadata and event (earthquake) parameters. A goal of the specification and implementation efforts is to present a common interface for data access across data centers. Another goal is to serve traditional seismological data users and a broader audience in geoscience and beyond. The latter is accomplished through the use of well-known and supported technologies that are not specific to seismology such as the ubiquitous HTTP and format containers like XML and simple text. This new common foundation has the significant benefit of promoting software reuse. The same data collection software can be used to access data at multiple data centers and software can be shared between data centers to implement the services. A small and broadly-supported subset of the HTTP standard is used by FDSN web services ensuring that users have a wide variety of options in terms of tools, programming toolkits, and support for accessing data. Since initial release of the specification in late 2013, the implementation of FDSN services at various data centers has progressed rapidly. As of this writing, nine seismological data centers[3] have implemented one or more of the interfaces with more implementations known to be in development. The benefits of these efforts are already apparent and multiple tools for accessing FDSN web services are now available. Furthermore, FDSN web services

increasingly serve as the backbone for data centers and systems accessing data from multiple data centers.

1. http://www.fdsn.org/
2. http://www.fdsn.org/webservices/
3. http://www.fdsn.org/webservices/datacenters/

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Community standard coming of age: Towards QuakeML 2.0

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QuakeML, a community-backed data model for seismic event parameter description, has been adopted as an FDSN standard in 2011, and developed into the gold standard for parametric data dissemination at seismological data centers since then. The current version 1.2, released in 2013, serves as as the default response format of earthquake catalog queries to FDSN web services.

The base of QuakeML is a UML data model. It is used in different manifestations, e.g., as a class model for software development, as a basis of SQL databases, or as an XML schema for data exchange. QuakeML has a modular architecture. Several thematic packages can be collected under a common umbrella.

Active community development on version 2.0 has been started in early 2015. At ETH, ORFEUS, and in the SeisComP3 ecosystem, SQL databases and program codes based on new thematic packages are in productive use (ground motion, site and station characterization, hydraulic parameters of borehole injection processes). A package for macroseismics has early draft status. The ORFEUS RRSM database is operated on the basis of SeisComP3 and its wfparam module, which implements the ground motion data model. For the InSight Mars mission, ETH develops a package for planetary quake location and characterization.

Documentation and discussion of the new packages has been started at the QuakeML wiki pages at http://quakeml.org/QuakeML2.0, eventually leading into an online Request for Comments process.

Taking advantage of its improved modularization and knowledge representation features, QuakeML 2.0 will allow the step from a successful exchange format for

earthquake source parameters to a data modelling paradigm for a broad field of parametric data use cases in seismology, and possibly beyond.

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The seismic broad band western mediterranean network and other instrumentation in the western mediterranean region.

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The Royal Spanish Navy Observatory (ROA) and the Complutense University of Madrid (UCM), with the collaboration of the GFZ of Potsdam, started to deploy a seismic broad band network in 1996, installing the SFUC station in south Spain. Since then, more and more stations were installed around Alboran sea and the Gulf of Cádiz.

This network, initially known as ROA/UCM, has been renamed as Western Mediterranean network (WM code) as new stations have been added outside Spanish territory and new partners were jointed (Evora University, Portugal; ISRABAT, Morocco; and GFZ).

Now a days, the WM network is composed by 14 BB stations, all of them with Streckeisen sensors, Quanterra or Earthdata digitizers and SeiscomP. There are 9 stations deployed in Spain (5 in the peninsula and 4 in North Africa places) with VSAT or internet communications, 2 in Portugal (one of them without real time), and 3 in Morocco (1 VSAT, 1 ADSL, 1 off line). Additionally, 2 stations more (one in south Spain and one in Morocco) will be installed along this year.

Indeed, the ROA has deployed a permanent VBB OBS at 2 km SW the Alboran Island linked to the island in real time by a 2 km optic fiber cable. Unfortunately, now a days this permanent OBS is stopped for maintenance, although it is planned to reinstall it along summer 2015. Also, a permanent GPS network have been deployed by ROA in the same area complementing the WM network.

Finally, ROA and UCM have an OBS pool composed by 6 broad band "LOBSTERN" OBS, three with CMG-40T sensor and the other three with Trillium 120. These OBS were tested along 2014, being deployed close to the Gibraltar Strait during 8 and 2 moths respectively. They will be deployed in September 2015 in SW of the San Vicente Cape for 8 moths as a part of the ALERTES-RIM project.

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Introduction of digital object identifiers for seismic networks

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Proper traceability and attribution for geoscience source data is important in promoting transparency and recognising the role of data providers in our community. The data sets produced by permanent seismic networks and temporary deployments are 'treasure troves' which now need to be traceable, citable and permanently locatable for research users. Current scientific practice is evolving to acknowledge this.
The EIDA and IRIS-DMC communities have worked together on development of methods for generation, maintenance and promotion of persistent identifiers for seismic networks. This resulted in a 2014 Recommendation by the International Federation of Digital Seismograph Networks (FDSN) on the use of Digital Object Identifiers (DOI) for seismic networks, including metadata suggestions. These DOIs can be cited equivalently to scientific papers, and tools such as DataCite allow the tracking of citations to these datasets.
The GEOFON, IRIS and RESIF data centres have already begun to roll-out these seismic network DOIs. This has involved working with principal investigators and network operators to prepare metadata consistent with the FDSN recommendation, preparation of landing pages, and changes to the web sites to promote DOIs where available. It has required improved descriptions of the data (metadata) and clarifying how individuals and institutions should best be recognised for their contributions to making the data available. We illustrate this process for a few representative networks. We are contacting additional network operators to help them establish DOIs for their networks.

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This is my abstract title: "Scanning and digitizing of historical analogue seismograms recorded by seismic stations of the Kyrgyzstan"

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The archive of the Institute of seismology of the National Academy of sciences of the Kyrgyz Republic (IS NAS KR) in Bishkek contains hundreds of thousands of historical analogue seismograms since 1927 from in total 166 seismic stations (permanent and temporary), which have been operated on Kyrgyz territory. The standard equipment at all these stations was Kirnos SKM-3 and SKD seismometers.

In the frame of a joint international project on capacity-building for CTBT verification between the IS NAS KR, the Institute of Geophysical Researches of the Committee of Atomic Energy of Kazakhstan (IGR CAE RK) and NORSAR (Norway) historical analogue seismograms of nuclear explosions conducted at different test sites of the world, are scanned and digitized. The project was initiated in 2013 and started in 2014. Until now more than 20,000 seismograms have been scanned with a resolution of 1200 dpi. In addition, more than 3,000 seismograms of nuclear explosions recorded by Kyrgyz stations since 1961have been digitized by IGR CAE RK staff, and then stored in the CSS 3.0 formatted database. This database is widely used for various studies about nuclear test monitoring.

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Searchlight correlation detectors: Optimizing seismic monitoring using regional and global networks

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The sensitivity of correlation detectors increases greatly when the outputs from multiple seismic traces are considered. For single-array monitoring, a zero-offset stack of individual correlation traces will provide significant noise suppression and enhanced sensitivity for a region surrounding the master event hypocenter. This region's extent is limited only by the decrease in waveform similarity with increasing hypocenter separation. When using a regional or global network, the zero-offset approach is only optimal when the master and detected events are co-located exactly. In many monitoring situations, events may be separated by up to many hundreds of meters while retaining sufficient waveform similarity for single-channel correlation detection. For extended source regions, a deployment of many beams for different hypothetical source locations in geographical space is required. The beam deployment necessary for optimal performance of the correlation detectors is determined by an empirical network response function which is most easily evaluated using the auto-correlation functions of the waveform templates from the master event. The correlation detector beam deployments for providing optimal network sensitivity for the North Korea nuclear test site are demonstrated for both regional and teleseismic monitoring configurations.

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Determination of 2013 North Korea nuclear test location using simulated annealing inversion method

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Simulated annealing inversion method was applied to determine the high precision location of the DPRK M5.1 February 12th, 2013 nuclear test. A local optimization technique can easily generate a solution by minimizing the error function, but the function depends on the initial model and does not necessarily reach its global minimum. Other methods such as simulated annealing can be applied to such global optimization problems because the convergence of the simulated annealing method is independent from initial model. We successfully determine the location of 2013 North Korea test site using simulated annealing inversion by using 15 regional stations. We showed the location of 41.277 N, 129.099 E, at 2.939 km depth and the RMS residual shifted from 0.820 (ISC-catalogue) to 0.07889. We also analyzed this result with the topographic data satellite imagery and compared with other methods. The proposed location have the 1469.04 m of elevation, -21.8429 mGal of bouguer anomaly, and 13.3985 mGal of second vertical derivative anomaly of gravity (shallow effect). This Simulated annealing inversion result is about 2.782 km from the high precision position proposed by Zhao et al. (2014) and 2.442 km from position by Zhang and Wen (2013).

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Broadband seismic array in Micronesia tropical zone in the western Pacific: Foward to understanding of multi-layer's interaction and tectonics

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Seismic signals include not only earthquake event but also the varieties of geo phenomena. Generally seismic station on ocean island records higher noise level signal due to ocean wave and worse site condition. In other hand, this condition means good monitoring window for oceanic status by seismological procedure. And tropical zone has daily stable weather more than middle latitude zone. Daily variation of atmospheric pressure is very similar in whole year. Significant signal is identified easily.

OHP/Pacific21 network operates about 20 stations by broadband seismograph, geomagnetic sensor and barometer systems in the western Pacific and south-eastern Asia. In these years, our group is focusing to Micronesia region covering sparse observatory area.
Last some years our group upgraded seismic stations and restarted measurement at two seismic stations of the Pacific oceanic islands, Marcus Island (MCSJ) of Japan and Majuro(MJR), Marshall islands as permanent stations.

Japanese group are deploying Broadband Ocean Bottom Seismometers array around Ontong-Java Plateau and Micronesia area, the southwestern Pacific for some years combining with permanent stations and new restarted stations. To fill island locations, we are operating more temporal stations at Chuuk(Truk) and Kosrae, Micronesia.

Our network project is focusing some topics. (1) Origin and developing process of Ontong-Java Plateau (2) Evaluation of real seismic activity in Guam-Yap-Palau trench zone and intra-oceanic plate of Micronesia (3) Ocean monitoring using by microseism and island tilting (4) Acoustic and seismic interaction of solid earth – ocean - atmosphere layers.

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Comparative noise performance of portable broadband sensor emplacements

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IRIS PASSCAL has supported portable broadband seismic experiments for close to 30 years. During that time we have seen a variety of sensor vaults deployed. The vaults deployed fall into two broad categories, a PASSCAL style vault and a Flexible Array style vault. The PASSCAL vault was constructed of materials available in-county and it was the Principle Investigator (PI) who established the actual field deployed design. The Flexible Array vault was provided to PIs by the EarthScope program, offering a uniform portable vault for these deployments. The vault consists of a 1.5 m diameter by 1 m tall piece of plastic sewage pipe buried with 10-20 cm of pipe above grade. A rubber membrane covers the bottom and cement was poured into the bottom, coupling the pier to the pipe. The vault is sealed and buried under ~30 cm of soil.

Cost, logistics, and the availability of materials in-country are usually the deciding factors for PIs when choosing a vault design and frequently trades are made given available resources. Recently a third type of portable broadband installation, direct burial, is being tested. In this case a sensor designed for shallow, direct burial is installed in a ~20 cm diameter by 1 m deep borehole. Our initial analyses suggest that direct burial sensors have lower noise levels on both horizontal and vertical channels across a range of periods spanning <1 s to 100 s.

Until recently vault performance for portable installations supported by the PASSCAL program was anecdotal. A formal comparison of these various installation techniques is the subject of this poster. We’ve selected a suite of experiments that are representative of the three installations and compare their noise performance by using PSD probability density functions (McNamara and Buland, 2004).

IASPEI (Seismology, Geophysics)

S11p - S01g/S11 Seismological Observation and Interpretation: The Future of the Global Seismic Infrastructures, Forensic Seismology and CTBTO Data

S11p-573

Instaseis: Instant global seismograms based on a broadband waveform database

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Spherical models for planetary bodies represent a common characterization of bulk global material properties. Our new methodology combines accurate seismic wave propagation, symmetry properties of radiation patterns, reciprocity, and high-order interpolation to deliver a **comprehensive waveform database**. From this, high-frequency record sections for a given model can be extracted within fractions of a second for **arbitrary source-receiver configurations**. The database thus acts as a once-and-for-all solution to wave propagation in spherically symmetric models.

Using reciprocity, 2 simulations with the global wave-propagation solver, AxiSEM (Nissen-Meyer et al. 2014, www.axisem.info), suffice to generate a complete database of Green's functions. The wavefield can be stored at all distances (0-180 degrees) and depths (0-700km for earthquakes) up to **1 Hz on roughly 2 TB**. Posteriori interpolation between GLL points ensures that seismograms from the database have the same accuracy as the numerical wave propagation solution. The ease of computation (10K CPU hours for 1 Hz) implies that multiple such databases may be computed for different models and stored on a small server. Applications include the efficient generation of reference synthetics for global tomography, wavefields for hybrid 1D-3D methods, source inversion and responses to finite-fault sources.
Instaseis offers a user friendly **Python interface** and directly integrates with ObsPy, it includes a GUI and **can run in a client/server configuration**, such that the databases can be accessed and shared via Internet.
A first example of such a database is being developed and stored at the IRIS DMC (Seattle) as a community service.

The corresponding Python code Instaseis can be downloaded from **www.instaseis.net**.

IASPEI (Seismology, Geophysics)

S11p - S01g/S11 Seismological Observation and Interpretation: The Future of the Global Seismic Infrastructures, Forensic Seismology and CTBTO Data

S11p-574

Ready for RfC: QuakeML data models for peak ground motion, station characterization, and site characterization

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Within the last years, several thematic extensions for the QuakeML data model have been drafted. Three of them, based on requirements of multiple stakeholders, got considerable peer review and productive implementations, so that they can be considered mature enough for a public Request for Comments process.

a) The Peak Ground Motion schema extends the Origin concept of the Basic Event Description package. It describes processed waveform snipplets and resulting strong motion descriptors, such as PGA, PSA, PGV, PGD, Arias intensity etc. This joint effort of the NERA NA3 partners is used in the waveform parametrization module of SeisComP3, and in the European Rapid Raw Strong Motion database.

b) The Station Characterization schema extends the Network-Station-Sensorlocation description of the GFZ InventoryXML with management information, descriptions of the geotechnical and built environment of seismic stations, and results of geophysical site assessment. Requirements are driven by NERA NA3 and the renewal of the Swiss Strong Motion network of the Swiss Seismological Service (SED). The ORFEUS and SED station books feature a SQL implementation.

c) The Site Characterization schema describes field measurement campaigns for different site characterization methods, such as noise arrays, H/V, active seismics, borehole logging, and SPT, along with raw data, analysis methods, and results (velocity profiles, H/V curves, amplification functions, dispersion curve ellipticity, quarter wavelength representation, SPT, drilling logs). The schema was initially developed in order to integrate all site characterization projects at SED, and subsequently extended to cover NERA needs for geophysical characterization of seismic station sites. It features SQL and Java implementations.

IASPEI (Seismology, Geophysics)

S02a - S02 50 Years of the ISC Service to Seismology

IUGG-1951

ISC data - long-term fundamentals of seismological research in Prague

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The ISC parametric data of seismic events provided to geosciences community carry essential information for a broad-scale scientific research. Systematic location of earthquake foci, determination of origin time and event magnitudes serve for monitoring Earth's seismicity (e.g., Kárník, 1968; 1996) or classification of energy released during the stress relaxation (e.g., Vanek et al., 1978). Moreover, the ISC data, including arrival times of different waves associated to individual earthquakes, has been intensively used in different studies of the Earth's structure, e.g., in seismic tomography (Babuška et al., 1990; Karousová et al., 2013), modelling the European lithosphere-asthenosphere boundary (e.g., Babuška and Plomerová, 1987; 2010) or morphology of convergent plate margins (e.g., Vanek, Hanuš, Špicák, 1978; 2007). The ISC catalogues/bulletins serve also as a platform for archiving/distributing information about weak local/regional events occurring in stable continental regions (e.g., West Bohemia –Vogtland swarm region) which thus become visible for a broader community. The ISC locations are also incorporated into the national seismological bulletins (http://www.czechgeo.cz/en/gfu-bulletin/). Though the modern research capitalizes on observations from temporary densely-spaced arrays of seismic stations and waveform processing, the parametric data provided by the ISC maintains its significance to the research. V. Kárník, J. Vanek and J. Plomerová contributed to the successful operation of the ISC as members of the Executive Committee in a period of 1978-2009. Irreplaceable feature of the ISC functioning is in providing the long-term continuity of the high-quality data, which is substantial for quality of scientific research in different fields of geosciences.

IASPEI (Seismology, Geophysics)

S02a - S02 50 Years of the ISC Service to Seismology

IUGG-2821

The role for the ISC in the 21st century

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As we celebrate 50-years of ISC service to the community there is an opportunity to look forward to the challenges and opportunities for the ISC in the 21st century. While the ISC is and will be the primary source of the long-term instrumental record of the Earth's seismicity, seismological networks and agencies are moving towards fast and reliable production of bulletins with real time waveform processing. This brings into question the utility of an ISC bulletin that is based solely on parametric data, one event at a time, and two-plus years behind real time. As such, the ISC must keep pace with technology and the needs of the community, and the ISC has the opportunity to fill an important role as an integrator of results that are produced by traditional, analyst-driven bulletins and bulletins that are developed by automated analysis. The ISC may also consider in-house analysis to quality check automated systems, as well as the production/integration of new types of parameter data, e.g. differential-time picks. New technologies such as travel-time predictions from 3D velocity models and the routine use of multiple event location methods should be introduced to ISC operations in the near to mid term scale. The ISC products introduced in the past few years, such as the IASPEI Reference Event List, the ISC Event Bibliography, the CTBTO link, and the ISC-GEM catalogue are already indispensable tools for scientific research, and broadening their scope and accuracy would further increase their importance. The ISC will also have to broaden its target audience to serve not only seismologists, but also the seismic hazard and risk, seismic engineering, and tsunami warning communities by introducing products specifically designed for the needs of the various disciplines.

IASPEI (Seismology, Geophysics)

S02a - S02 50 Years of the ISC Service to Seismology

IUGG-2841

The international seismological centre: Ancestry and origins

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The founding of the International Seismological Centre just over 50 years ago marked, not an innovation, but a continuity with a record of global earthquake reporting that began in 1899 with John Milne's "Shide Circulars". These early bulletins, published with the support of the British Association for the Advancement of Science, were issued from Milne's home in the Isle of Wight until his death in 1913. The continuation of Milne's work was put on a secure basis at the end of the First World War at the first IUGG General Assembly in 1922, with the work undertaken by the newly-constituted International Seismological Summary, under the direction of HH Turner at Oxford. By the end of the Second World War, the ISS bulletin was being prepared virtually single-handedly by Ethel Bellamy, and with the worldwide increase in the number of stations, was considerably in arrears, and in financial difficulties. The decision to replace the ISS with a new body to take charge of producing definitive global earthquake locations was taken at a UNESCO meeting. This new "World Centre" for seismology (as it was referred to) became the ISC. It was agreed that it would be located in the UK, but it would be funded and controlled internationally. The location was agreed to be Edinburgh, with Patrick Willmore, who had taken over direction of ISS from Robert Stoneley, its first director, which conveniently emphasised the continuity between ISS and ISC. The first ISC annual bulletin was for the year 1964; the last two years of ISS data, 1962 and 1963, were actually published by ISC.

IASPEI (Seismology, Geophysics)

S02a - S02 50 Years of the ISC Service to Seismology

IUGG-3050

Global data centres as a shared responsibility - a 50-year-long miracle at the International Seismological Centre

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The ISC performs a public good by compiling earthquake information from global, national and regional reporting agencies, computing and maintaining the global database of earthquake parameters, and by refreshing the set of solutions as new data or processing algorithms become available. The ISC data make an important contribution to research of the Earth's seismicity, tectonics, inner structure, seismic hazard and risk, monitoring CTBT and education. Today, the ISC's preliminary bulletin is available for events of 2015, and the reviewed bulletin for 2012. In addition, station readings are now available for post-1904 earthquakes as a result of the ISC-GEM catalogue initiative. All products are freely and rapidly available through the web. There are two challenges to this public good: 1) acquiring the data and its metadata and 2) paying for the operations of the ISC. Regarding the data, the ISC accepts all seismograph readings, but there is continual need to search out new network operators and to encourage laggard contributors. Data from large areas of the globe are still scant. Note there is no obligation on the data providers to support the ISC financially. Secondly, most of ISC's budget comes from voluntary annual contributions and these are continually under threat. It is a tribute to the ISC's past directors that contributions have been maintained over the past 50 years, though it is an ongoing struggle. This is especially true in the case of contributions from commercial companies that have difficulty appreciating the concept of "openly available products". The ISC is grateful to its past and present contributors!

IASPEI (Seismology, Geophysics)

S02a - S02 50 Years of the ISC Service to Seismology

IUGG-3951

ISC 2015: Mission and rebuild of the bulletin

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The International Seismological Centre (ISC) is a non-governmental non-profit-making organization funded by 62 research and operational institutions worldwide. Since its original setup in 1964, the mission of the ISC has considerably evolved. In addition to production of the Bulletin, the ISC now also maintains the International Station Registry, EHB and GT datasets, the ISC-GEM Catalogue, the Event Bibliography and the International Registry of Contacts in Seismology. Most important recent development is the rebuilding of the Bulletin - the ISC’s flagship product. Over the last 5 years we included a number of previously unavailable bulletin datasets from permanent and temporary networks worldwide, corrected known errors and inconsistencies, recomputed all ISC hypocentre solutions with ak135 velocity model and the new ISC location algorithm, reassessed the magnitudes values and assigned the primary (for each event) and preferred (for each type) magnitudes. In addition, we increased the coverage of the ISC Bulletin from ~55 to ~110 years (1904-2015) by including the hypocentre solutions, mb/MS magnitudes and, most importantly, the station arrival times and amplitudes digitized from the original paper-back station bulletins of the early instrumental analogue period. Finally, we hope that the entire suite of improved and freely distributed ISC data will continue to be in demand in many fields of geophysical research.

IASPEI (Seismology, Geophysics)

S02a - S02 50 Years of the ISC Service to Seismology

IUGG-4480

50 years and counting: Past and current collaborations between the International Seismological Centre and the National Earthquake Information Center

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The International Seismological Centre (ISC) and the USGS National Earthquake Information Center (NEIC) have a common goal of providing the community with curated global earthquake catalogs for use in scientific studies and assessment of earthquake hazard and risk. During the ISC's 50 year history, the relationship between ISC and NEIC have served to improved both institutions' products and combined service to the community. Through regular coordination meetings with our institutions and the European Mediterranean Seismological Centre, we have improved the timeliness and content of our catalogs by maintaining efficient data sharing and setting of uniform standards (e.g. station code assignment and event-type description). The USGS has also supported targeted efforts of the ISC such as the continued development of the ISC-GEM catalog. The NEIC has used ISC's more comprehensive archive of arrival times and amplitude measurements to test and validate new location techniques and assess the impact of different measurement procedures on magnitude calculations. We will present a history of this mutually beneficial relationship. A current NEIC focus is on services that go beyond the content of traditional seismological bulletins: real-time processing and production of source parameters and rapid estimation of earthquake impact. We will provide specific examples of NEIC's use of ISC data to improve our operations, including the testing of multiple-event location techniques using 20,000+ earthquakes in Alaska and Chile and comparisons of amplitude-based magnitude calculations.

IASPEI (Seismology, Geophysics)

S02b - S02 50 Years of the ISC Service to Seismology

IUGG-1176

Studying collision and subduction mechanisms based on regional tomographic inversions of the ISC data

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The International seismological center (ISC) provides a large database with millions seismic wave travel times corresponding to stations and earthquakes distributed worldwide. For decades, these data have been used by many to build global and regional tomography models. Using the ISC data is most efficient for studying collision and subduction zones where the majority of the worldwide seismicity occurs and enables very dense data coverage. In this presentation, an overview of various regional tomography models of the upper mantle beneath several subduction and collision zones will be presented. Beneath the Kuril-Kamchatka arc, the tomography models reveals changing of the slab shape which is interpreted as a transition from the “pull” to “push” driving mechanism of subduction. Beneath Taiwan, the tomography model images two oppositely oriented subduction zones. At a junction point, these subductions give very strong compression rate resulting at strong shortening of the crust in the Taiwan Island. In the Mediterranean region, regional tomography study reveals very complex structure of the African Plate subduction and interaction with European structural elements. For example, beneath Apennines, a sausage shaped anomaly is observed which is interpreted as delamination of Adriatic lithosphere. In continental collision zones, the tomography models show complex interactions of lithosphere blocks and delamination of mantle lithosphere. Examples of tomography results for Pamir-Hindukush and Caucasus will be presented.

IASPEI (Seismology, Geophysics)

S02b - S02 50 Years of the ISC Service to Seismology

IUGG-1898

Origin of scattered phases in the coda of the core phases PKP(BC) and PKP(BCdiff)

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The PKPbc and PKPbc-diff coda frequently contains energy arrivals that do not correspond to any known seismic phases in reference 1D earth models such as AK135 (Kennett et al., 1995). We have assembled a global dataset of several thousands high quality records of core phases in the distance range 149-178^{o} and found that an energy wavepacket is present in 70% of them about 5-20s after PKPbc or PKPbc-diff with no obvious geographical pattern. We use array analysis techniques to enhance this signal and characterize it, in order to try and understand its origin, as well as accurate source locations from the EHB (Engdahl et al., 1998) and ISC catalogs. We show that it arrives along the great circle path, and corresponds to a narrow range of ray parameters. There are no systematic variations with source or station locations, nor with the depth of the source. We rule out an origin in the mantle and show that the most likely origin is in the vicinity of the inner core boundary. We discuss the possibility that it might be due to structure in the F-layer, although, alternatively, lateral variations in the character or topography of the ICB may be involved.

IASPEI (Seismology, Geophysics)

S02b - S02 50 Years of the ISC Service to Seismology

IUGG-2260

Application of the data from the Bulletins of the International Seismological Centre to studies of the Earth's three dimensional structure

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The idea to use the travel times from the ISC Bulletins in an attempt to recover the very long wavelength 3-D velocity anomalies in the lower mantle was put forward in 1974. At that time processing was completed only for the first seven years of the ISC operations (1964 - 1970). and although available on magnetic tapes, they were stored in essentially free format, so that extraction of the data from the tapes represented the paramount technical problem.Some 700,000 travel time data were extracted for selected events. Parameterization was very coarse: five depth shells, with each shell divided into 30 blocks for the total of 150 parameters; the memory of computers available at that time did not allow for more. The first 'no-name' 3-D model published in 1977 showed an increased level of heterogeneity in the deepest shell (2200 km - CMB). Expanding the model in spherical harmonics and assuming that density and velocity anomalies are proportional allowed for computation of a 'synthetic geoid'. Correlation of the synthetic and actual geoid was shown to be significant for degrees 2 and 3, with most of the synthetic signal originating in the lowermost shell. The result has been confirmed by later studies involving many more Bulletin-years.
Other discoveries enabled by the ISC data are those of the inner core anisotropy (1986), with the axis of the hexagonal symmetry parallel to the Earth's rotation axis and the existence of the 'inner-most inner core' (2002) with the anisotropic parameters being distinctly different in the innermost 300 - 500 km of the Earth. The issues related to the inner core anisotropy are highly controversial, but the ISC data are very important because of the superior ray-path coverage in comparison with the broad-band digital stations.

IASPEI (Seismology, Geophysics)

S02b - S02 50 Years of the ISC Service to Seismology

IUGG-2765

Using ISC data to image Earth's interior

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The service of the ISC to the seismological community extends far beyond production of the definitive bulletin of Earth's seismicity. The millions of events and associate arrival-time measures (picks) archived at the ISC form the vast majority of data used in global P-wave tomography studies. These data have been compiled over decades of effort, which include: inviting regional networks to contribute data, helping network operators standardize metadata and improve measurement quality, and ultimately integration of data in a variety of formats into what becomes the ISC bulletin. In seismic tomography studies, data have typically been extracted from the ISC, culled by removing outliers, and events relocated. More recently the Bayesloc method has been used to simultaneously relocate events and assess data quality. Approximately 96% of ISC picks pass the rigorous Bayesloc analysis. Relocation of events in Bayesloc includes travel time corrections to the standard 1D global model, and the resulting epicenters shift by an average of 6.8 km. The shift direction tends to be consistent for event clusters, suggesting that unaccounted earth structure can bias bulletin locations. Bayesloc data analysis and relocation reduces travel time residual standard deviation from 1.59 seconds to 1.26 seconds, which is a 37% reduction in variance. Our tests show that images of Earth's interior benefit greatly by ISC's data collection efforts and post processing helps to sharpen the image.

IASPEI (Seismology, Geophysics)

S02b - S02 50 Years of the ISC Service to Seismology

IUGG-3313

Two sets of twenty-five years of ISC Delay times and their newly estimated uncertainties

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Twenty-five years ago, about twenty five years worth of ISC P wave delay times proved surprisingly powerful in imaging the Earth's lateral heterogeneity, first on a regional scale and in the upper mantle, but soon followed by global heterogeneity models for the whole mantle. ISC delay times were the critical component in the discovery that slabs of subducting oceanic lithosphere sink deeply into the lower mantle. About 15 million P wave delay times had been collected by the ISC during its first 25 years. However, in the twenty-five years that followed the ISC collected about 100 million P wave delay times. We exploit this sixfold-increased volume of delay time data to estimate geographically varying uncertainties in delay times in the ISC bulletins. To this end we cluster ISC delay times by earthquake and station regions, then trace rays between them to set up a linear system of equations as typically used in earthquake location procedures and in delay time tomography. This system is then analyzed with the method of Voronin et al. (GJI, 2014), which utilizes a singular value decomposition to separate the few most significant components of the system from the more numerous, less significant ones. We utilize the less significant ones to estimate uncertainty levels in the ISC delay times. We compare the geographically varying uncertainty levels in ISC data with uncertainties in an interactively picked global data set of delay times. In addition we explore how current models of mantle heterogeneity have improved compared to one of the original models derived from ISC data.

IASPEI (Seismology, Geophysics)

S02c - S02 50 Years of the ISC Service to Seismology

IUGG-1479

Seismic travel times and event location

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The aim of characterising seismic events requires that both the location and nature of the event be known. To extract the hypocentre in 3-D space and time requires some model of seismic wave propagation, and an appropriate way to handle information from multiple observation points. The location problem can be strongly nonlinear and so directed search methods can be effective in getting good estimates from which conventional error parameters can be assessed.
The ISC has progressively improved its location procedures, whilst sustaining continuity in event information. Currently the procedure uses the global ak135 model to estimate times. This 1-D model was designed to fit empirical travel times, from the station network and so combines continental and subduction zone character. Improved depth resolution comes from a fortunate choice of upper mantle structure that reconciles the direct and surface reflected phases.
The Earth is heterogeneous in 3-D and the weaknesses of a single model are rather evident for oceanic events well away from a subduction zone, which deserve separate treatment. It is possible to account for the major efforts of continental heterogeneity, e.g. fast cratonic structure, with practical location in 3-D as demonstrated for Australia. Full 3-D analysis needs a delicate balance in the representation of structure so that adequate detail is included, but not too much. In this regard data mining in the event archive may be helpful, so that prior structural information can be exploited directly rather than through the mediation of an Earth model.

IASPEI (Seismology, Geophysics)

S02c - S02 50 Years of the ISC Service to Seismology

IUGG-2666

Reducing magnitude bias using station thresholds derived from ISC amplitude/period data

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The magnitude of a seismic disturbance is a simple measure of the energy released, and plays a crucial role in forensic seismology in estimating the yield of an explosive device. Magnitudes at several stations are aggregated to determine network magnitude, because a single station has a bias of amplitude, attributed to attenuation and scattering in the nearby crust and upper mantle. The usual aggregation, an arithmetic mean, implicitly assumes a symmetrical distribution of station magnitudes. This is violated when no amplitudes are reported from stations where the signal was hidden in noise, causing the mean to be biased higher than the "true" magnitude of the disturbance. A procedure to reduce the bias involves maximum-likelihood determination of the network magnitude, using noise threshold values for those stations that were working but did not report an amplitude. The noise threshold value for each station can be determined from bulletin amplitude data for that station, by fitting a Gutenberg-Richter magnitude-frequency law truncated at low magnitudes. We used the comprehensive ISC bulletin to determine thresholds for stations that detected presumed underground nuclear explosions (1964-1996), so that we could invert jointly for reduced-bias mbs and station correction terms. Earthquake mb can also be redetermined for large subsets of the ISC bulletin, allowing accurate determination of regional Gutenberg-Richter "b" values. Gradual or abrupt variation of station thresholds with time can be recognised in the long series of ISC bulletin data.

IASPEI (Seismology, Geophysics)

S02c - S02 50 Years of the ISC Service to Seismology

IUGG-3332

Exploring and exploiting the ISC arrivals database: Station corrections for rapid and reliable earthquake location

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For effective earthquake and tsunami early-warning it is crucial that key earthquake parameters are determined as rapidly and reliably as possible. This requirement entails that initial estimates of earthquake locations will be based on a minimal data set, with the risk of large errors and bias in epicentre and hypocenter depth, or detection of a false event. The use of station travel-time corrections is a basic and important tool to avoid these problems.

At the INGV CAT* tsunami alert center, Early-est** is the module for rapid determination of the location, depth, magnitude, mechanism and tsunami potential of an earthquake. Early-est produces fully automatic results and their uncertainties using as few as 3 to 5 P onset observations.

Here we use the ISC bulletin arrival database to develop empirical, station travel-time corrections for the ak135 velocity model to improve routine, real-time location in Early-est. We use the R statistical computing and graphics language to explore, exploit and visualize the ISC arrival database and to map the obtained station corrections. We analyze and discuss the station corrections with regards to epicentral distance, source depth, tectonic setting and crustal structure, and their effect on location accuracy.

* CAT, “Centro di Allerta Tsunami”, part of the Italian, candidate Tsunami Service Provider ** Early-est (EArthquake Rapid Location sYstem with EStimation of Tsunamigenesis)

IASPEI (Seismology, Geophysics)

S02c - S02 50 Years of the ISC Service to Seismology

IUGG-3545

Can seismologists handle the truth? From ground truth to calibrated earthquake locations

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By the 1980s institutional programs to routinely locate earthquakes worldwide and to freely disseminate hypocenters and associated phase arrival times were well established. The International Seismological Centre (ISC) was at the forefront of such efforts. Seismologists in the late 1990s became concerned with understanding the sources of location bias and minimizing their effects. An important early improvement was the introduction in 1998 of the EHB method of analysis (emphasizing good azimuthal coverage and use of depth phases) and the associated global catalog. Researchers in the CTBT community embraced the concept of “Ground Truth” (GT) locations. The concept of GT in seismology evolved far from the original application to engineered explosions and earthquakes with exceptionally dense and close station coverage. For instance, the GT definition relates only to epicentral accuracy, but a full understanding of hypocentral accuracy is needed for many studies. We argue that it is time to move beyond the GT terminology and instead develop the concept of “calibrated” hypocenters, i.e., those that have been determined with methodologies that are specifically designed to identify and minimize the sources of systematic location error, as well as providing realistic uncertainties to all four hypocentral parameters. We describe one such method, based on a combination of two different approaches to multiple event location. A new nomenclature is required to support such research, one that includes uncertainty in focal depth and origin time. The data sets assembled and distributed by the ISC have been of immeasurable importance to research in this subject, and we anticipate that close cooperation with ISC personnel will continue to be a central element of this research effort.

IASPEI (Seismology, Geophysics)

S02c - S02 50 Years of the ISC Service to Seismology

IUGG-5352

Revisiting 50 years of ISC data: Worldwide improvement in earthquake locations and seismic monitoring capabilities

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The complete ISC Bulletin is used to systematically improve the locations of earthquakes worldwide and to provide a framework for improving global seismic monitoring capabilities. An iterative, multistep relocation procedure is applied to the Bulletin's approximately 90 million phase arrival times of 3.5 million earthquakes. These procedures initially correct for large location errors and unresolved depths often present in the ISC Catalog, followed by a simultaneous inversion of phase delay times to increase location precision. An efficient, multi-scale, double-difference algorithm is used to solve for relative hypocenter locations to the precision of a few km or less in many regions, while incorporating absolute location constraints from catalogs such as EHB, GEM, and other ground truth information. The current globalDD catalog includes close to one million earthquakes, equivalent to approximately 70% of events with 10 or more picks. Additional iterations are being carried out that aim at including less well constrained events and precise delay times from waveform cross-correlation. The current relocations significantly sharpen the view of seismicity around the world, in particular in regions where event density is high, such as subduction zones, but also along mid-ocean ridges where existing hypocenters are especially poorly located. The high-resolution location results demonstrate the unique and important value of the ISC Bulletin in investigating earthquake processes and the evolution of fault structures over several decades at the scale of a few kilometers along entire plate boundaries. Additionally, these results provide the underlying data for real-time, high-precision monitoring of future global earthquakes using large digital seismic archives.

IASPEI (Seismology, Geophysics)

S02d - S02 50 Years of the ISC Service to Seismology

IUGG-0302

Long-term detectability of teleseismic events and their relation to surface environment at Syowa Station, Antarctica

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Seismic phase identification of the teleseismic events at Syowa Station (SYO), Antarctica have been carried out from 1967 since the International Geophysical Year (1957-1958). Based on the development of telecommunication links between Antarctica, digital waveform data are transmitted to the National Institute of Polar Research (NIPR) for utilization of the phase identification. Arrival times of seismic phases have been reported to the International Seismological Centre (ISC), and published as the 'JARE Data Reports' from NIPR. The reported teleseismic and local signals have sufficient quality for many analyses on dynamics and structure of the Earth’s as viewed from Antarctica. In this presentation, time variations for detected teleseismic events are summarized over the last four decades in 1967-2010. Characteristics of the events, magnitude dependency, spatial distributions, seasonal variations, as well as a classification by focal depth are demonstrated. In addition to increase in number for the occurrence of teleseismic events over the globe, a technical advance in observation system and station infrastructure, together with an improvement of procedure for reading seismic phases, could efficiently be combined to produce the total increase in detection number in last few decades. Variations in teleseismic detectability for long-term is also associated with meteorological environment and the sea-ice spreading extent around the Antarctic continent. In the presentation, a long-term variation of teleseismic events is focused in particular involving surface environmental changes that are identical in the Antarctic. From statistical analysis, moreover, air temperature variation contributes significantly on annual variation in detection capability.

IASPEI (Seismology, Geophysics)

S02d - S02 50 Years of the ISC Service to Seismology

IUGG-4317

Using the ISC earthquake catalogue for earthquake hazard analysis

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The ISC Bulletin is produced using data from most of the key seismograph networks in the world, listing parametric data and earthquake location and magnitude results for all earthquakes with at least one location, with acknowledgement. Many smaller earthquakes are recorded by a single network, and these data and results are included alone. Larger earthquakes have data from multiple sources, so the ISC merges and re-analyses data, giving an additional ISC solution. The ISC plays a large part in standardising methods used to determine parameters, especially magnitude. Centralised merging of data and re-analysis saves the member observatories from much repetitious analysis, and the need to provide distribution systems.

The ISC Bulletin is the most comprehensive source of parametric earthquake data available for hazard studies, usually with the best available locations, magnitudes and mechanisms.

However, it does not give declustering information (foreshocks and aftershocks), data or results from non-contributing networks or from studies by individuals, and does not yet include the recent significant re-analysis of locations and magnitudes published in the ISC-GEM catalogue. Preferred magnitude values (ML, mb, Ms, Mw, or Me) are sometimes unclear if not ISC results.

Most observatories maintain their own list of local earthquakes, often derived using local velocity models. A database such as the author's GGcat, largely based on the ISC data but including this additional information, simplifies practical hazard analysis.

To compare hazard studies, it is desirable that a specific catalogue should be available for all to use. Perhaps the ISC could consider publishing an annual update that includes any additional data of past events, and new results from improved analysis methods.

IASPEI (Seismology, Geophysics)

S02d - S02 50 Years of the ISC Service to Seismology

IUGG-4351

The ISC data and temporary network observations

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In many regions, the problem of seismic hazard assessment can not be accurately solved without the ISC data being the most reliable and homogeneous information for world seismicity during last 50 years. These data become especially important in regions, where regional/national seismic networks are absent or recently installed. Even accurate but short-term data of dense temporary networks can not fully replace the long-term ISC data.
Aftershocks provide important information on strong earthquake source geometry and seismic regime of the entire source zone. This information is the basis for the development of source physics and hazard evaluation after the earthquake. Usually in the epicentral area, the dense temporary seismic network is installed, which provides accurate data on source geometry. But it takes time to install such network, thus the most important information immediately after the mainshock is missing. ISC data is the most reliable source of information for, so called, first aftershocks.
The examples of using ISC data in the problems above and combining them with data from temporary networks are given.
The study was partly supported by the Russian Foundation for Basic Research, project no. 14-05-00258.

IASPEI (Seismology, Geophysics)

S02d - S02 50 Years of the ISC Service to Seismology

IUGG-4381

Missing, duplicates and fakes: Not just macroseismic events

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Re-analysis of catalogues of old macroseismic events show the presence of previously mislocated events, as well as duplicated or even fake ones. But, not always properly acknowledged, this situation is found also for instrumentally located events.

Project INSPIRE, funded by Portuguese FCT, has been developed since 2012 and it aims to review the instrumental seismicity of Portugal in the period 1900-1960. As it includes also the Portuguese archipelagos, it covers a large surface, including the Nubia-Eurasia suture zone between Azores and Gibraltar.

Several factors make particularly difficult the relocation of the events in this period, including the poor sensitivity of the seismographs, the small number of stations available, and also the incompleteness of the reports and low accuracy of chronometers. Furthermore, the absence of seismic stations on large areas of the Atlantic Ocean introduces further uncertainties.

Based on the data published in the International Seismological Summary (ISS), a throughout revision of the seismicity of this zone, complemented with information obtained from station seismic bulletins, seismograms and related documents, has been performed. It allowed discovering earthquakes ignored up to now; but also to detect events mislocated, duplicate and even fake events presently included in the ISC database. Examples of all these cases will be presented.

These results, not affecting to the largest earthquakes, concern events with magnitudes around M5 and even M6 and point to the necessity of a throughout review of the ISC files. However, the amount of work and characteristics of the research points also the suitability to distribute such task at regional levels, ISC acting much more as coordinating and homogenizing unit and steering institution.

IASPEI (Seismology, Geophysics)

S02d - S02 50 Years of the ISC Service to Seismology

IUGG-5018

The ISC-GEM catalogue: examples of application in global and regional contexts

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The ISC-GEM catalogue (Storchak et al., 2013; Storchak et al., 2014) is an instrumental seismicity catalogue created in the framework of a project sponsored by the Global Earthquake Model initiative - by the International Seismological Centre in collaboration with an international team of experts. The ISC-GEM catalogue possesses unique features in terms of homogeneity and uniformity, as location and magnitude of each event have been determined following the latest state-of-the-art procedures adopted by the ISC (e.g. Bondar et al., 2014). The improvements in location accuracy provide seismologists and geologists with a better constraint of both the spatial geometry and seismic history of many active fault and subduction systems, even in parts of the globe where local networks may be sparse or have a short operational history. A pool of organizations is currently supporting an extension of the catalogue to include occurred after 2009 and within magnitude-time windows not covered in the first version of the catalogue. This extension incorporates more events from the 20th century, lowering the threshold of magnitude completeness and improving the accuracy of the hypocenter locations and event magnitudes in the pre-ISC era. In this communication we illustrate some examples of utilization of the ISC-GEM catalogue within global and regional research and also in the development of source models for hazard analysis and we outline some possible ideas on future developments.

IASPEI (Seismology, Geophysics)

S02d - S02 50 Years of the ISC Service to Seismology

IUGG-5781

Use of ISC data to improve earthquake hypocentral locations: HinduKush and Indonesia

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We show that hypocentral locations can be improved by using ISC phase data and have applied it to the Hindu Kush and the Indonesian regions. In the Pamir-Hindu Kush region, ~6000 shallow earthquakes were relocated using ISC-reported P, S and depth phase arrival times using the JHD technique. The improved delineation of the seismogenic zone suggests that the intermediate depth seismicity in the Pamir-Hindu Kush region is most simply explained by a single S-shaped seismic zone, 700 km long and no more than 30 km wide with most activity concentrated at 100-300 km depth and which has overturned beneath the Pamirs. This is interpreted as a remnant piece of oceanic crust that became neutrally buoyant and now hangs in the mantle underneath the active mountain belt (Pegler & Das, GJI, 1998; Pavlis & Das, Tectonics, 2000). Along the entire approx. 2600 km long Indonesia subduction zone, we used ~9400 handpicked P, S, pP, sP, PcP and ScP phases from digitally recorded seismograms, together with ISC reported phases, to obtain improved hypocentral locations for ~2600 earthquakes, in the period 1962--September 1996 for earthquakes deeper than 50 km. We show use of the core-reflected phases is as good as use of depth phases, and since such core phases often have larger amplitudes and sharper onsets than the depth phases, their arrival times can be read very accurately, both giving smaller location errors than the use of P waves alone (Schöffel & Das, JGR, 1999; Das, JGR, 2004). We show that a portion of the Indonesian arc between ~110°E and 123°E longitude, and deeper than ~500 km, is dipping southward at an angle of ~75°, in a direction opposite to the upper part of the north dipping slab, suggesting southward lateral flow in the mantle, relative to the plate motion vector here. The seismicity distribution is very non-uniform both along the arc and in depth, with a gap in seismicity along depth in most places of the arc. The depth of the upper edge of the gap varies from 100-450 km and its lower edge from 350-670 km in different portions of the arc. The very wide seismic zone in the 100--200 km depth range between 129--131°E is situated at the highest curvature of at the easternmost portion of the arc, has the highest seismic activity, and is the only part of the arc with earthquakes continuously occurring from the surface down to below 600 km.

IASPEI (Seismology, Geophysics)

S02p - S02 50 Years of the ISC Service to Seismology

S02p-579

About ISC Database mirror in Earthquake Research Institute

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The Earthquake Research Institute (ERI) maintained a database mirror with International Seismological Center (ISC) from February 2010. ERI re-build database and make indexes of the ISC database from the dumped text data that saved in DVD-R when we visited to ISC on 2010. ERI updated the database mirror of ISC by Slony-I protocol considering with network band between ISC and ERI. The update is basically carried out once a day and we confirm the number of the records of both database fields after mirroring process. In past 4-year operation, database mirroring is carried out without problems except two times hard disk troubles of mirroring host. From our experience, when a network band is limited, it can conclude that it is very effective and stable to carry out database mirror by Slony-I protocol. ERI converted to the catalogue format of ERI's tool from ISC database mirror using SQL search query. Then, we offered ISC catalogue data with World Wide Web pages of Seismicity Analysis Tool: TSEIS (http://wwweic.eri.u-tokyo.ac.jp/tseis/isc/) which developed in ERI. TSEIS system has many functions of hypocenter map, magnitude time plot, cumulative number time plot, cross section plot and focal mechanism plot etc. by inputting web forms. The usage of this web tool increases year by year, and this system was provided more than ten years.

In the near future, we will add a function of global standard seismicity analysis algorithm such as Epidemic Type Aftershock Sequence (ETAS). We will also develop the direct access to ISC database mirror from TSEIS system.

IASPEI (Seismology, Geophysics)

S03a - S03 Recent Large and Damaging Earthquakes

IUGG-0773

The focal property of the 2014 Ms6.5 Ludian, China earthquake sequence

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On August 3rd, 2014, an Ms6.5 earthquake struck Ludian district in Yunnan province, China. Although the magnitude of this earthquake is relatively small, it caused serious disasters with at least 617 people died, 112 people missed and lots of houses collapsed. In order to better understand the seismogenic structure and the seismic risk of the source region, we collected broadband seismograms from seismograph network in Yunnan and its surrounding provinces, and applied CAP method to grid search the focal mechanisms and centroid depths of the mainshock and its strong aftershocks. And the rupture process of the mianshock was investigated based on finite fault inversion method. The result shows that the Ludian earthquake is a left-lateral strike slip earthquake, with magnitude of about Mw6.1. Combined the focal mechanism solutions of the mainshock and the strong aftershocks, as well as their spatial distributions, we deduced that the mainshock should be occurred on the NNW trend Baogunao-Xiaohe Fault (BXF). Based on the tectonic environment, the BXF should be a secondary conjugated fault of the Ludian-Zhaotong Fault (LZF) which was affected by the Ludian Earthquake and its seismic risk should be paid highly attention to. The optimized centroid depth of the mainshock is 3km, also the depth at which the maximum slip occurred, which might be the main factor that caused such serious disaster besides poor building quality and landslides triggered by steep topographic relief.

IASPEI (Seismology, Geophysics)

S03a - S03 Recent Large and Damaging Earthquakes

IUGG-1083

Characterizing the spatial features for the aftershocks of the Wenchuan Earthquake (M8.0, 2008, China)

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A catalogue with 93836 events were obtained by a seismic network during a 4-year period after the M8.0 Wenchuan Earthquake on May.12, 2008. The events were located by China Earthquake Networks Center with average crustal velocity model and without relocation afterwards. The active images of the aftershocks moving on a map showed that from the 4 months after the mainshock the aftershocks turned to be stochastic in spatial distribution. During the first 4 months, the reciprocal of frequency varied linearly with time. The aftershocks distributed in a 10-30km width belt along the main fault within 10 days after the mainshock, and after the 4th month, the belt maintained 30-100km width till now. Spatially, the aftershocks distributed from the focal place to the northeastern end of the rupture within 1 day after the mainshock, and till 10 days after, the aftershocks covered almost all the thrust main fault. Another interesting case is that only within 6 hours, the distribution of aftershocks appeared to concentrated on 3 sessions of the fault, and the farthest session was about 200km away from the epicenter of the mainshock, where the largest aftershock (M6.5) took place in 12 days later.

IASPEI (Seismology, Geophysics)

S03a - S03 Recent Large and Damaging Earthquakes

IUGG-1091

Characterizing the temporal features for the aftershocks of the Wenchuan earthquake (M8.0, 2008, China)

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A M8.0 earthquake took place on the Longmenshan fault in the May of 2008 in south-east China, which is named as the Wenchuan Earthquake, and a 4-year long earthquake catalogue was obtained after the mainshock. From 14:28:0.4 on May 12, 2008 till 23:18:50.5 on May 12, 2012 of Beijing local time, 95240 aftershocks were recorded in a rectangle area of 102°E-105°E, 30°-34°E, and finally 93836 events were located. In this catalogue, there were 25747 events with M≥2.0 and 7 events with M≥6.0. b values were calculated for this catalogue for different time steps and different magnitude ranges. Results showed (a) the average b is 0.8340±0.0764 in a 4-year long time window, and the b values turned to be on a line for M3.0-M5.0 quakes. (b) the b values with a 30-day window and 1-day step turned to be pseudo-periodic, and the amplitudes turned larger and larger especially after 1 years from the mainshock. (c) b values varied in a small range of 0.8-0.83 after the August of 2008, and turned to be stable after the June of 2009, which means that the earthquakes along the ruptured faults within 120 days could be related to fault recoveries and the events after 1 year from the mainshock may only be local strain adjustment and display no more significant tectonic meaning for fault activities.

IASPEI (Seismology, Geophysics)

S03a - S03 Recent Large and Damaging Earthquakes

IUGG-1105

The April 20, 2013, Lushan, Sichuan, China, earthquake: seismogenic model by multidisciplinary ‘evidence chain’

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The April 20, 2013, Lushan, Sichuan, China, M_S7.0 earthquake is one of the significant earthquakes in China. The seismo-tectonic picture of the Lushan earthquake is clear at the scales of lithosphere plate and crustal block, but remains puzzle at the scale of seismogenic faults. Complex was that the southern Longmenshan fault zone has four nearly parallel main faults striking northeast, the thrusting geometry of which makes the associate of the earthquake source with a fault complicated. In the field, there was no surface fault observed. This conclusion is based on the ‘evidence chain’ from systematic geological survey which includes fault mapping, trench detection, and shallow profiles of seismic sounding, to the inversion of seismic and strong ground motion data for the slip distribution, and further to the distribution of aftershocks by DD location. Associate of the seismic source with a known or unknown fault needs accurate location of the event and precise mapping of the active faults. The ‘evidence chain’ for this associate is from the back-projection of seismic wave field which obtained the accurate location of the mainshock, to reflection seismology which retrieved the seismic velocity profile crossing the epicenter area, further to the pattern of ground deformation and the relocated aftershock distribution pattern. The multi-disciplinary ‘evidence chain’ indicates the Lushan earthquake was produced by a blind thrust fault to the east of a branch of the southern Longmenshan fault which was thought to be the seismogenic fault in the early stage of earthquake emergency. The seismogenic model reveals that, different from the 2008 Wenchuan earthquake, the earthquake preparation process of the Lushan earthquake seems more closely related to the Sichuan basin.

IASPEI (Seismology, Geophysics)

S03a - S03 Recent Large and Damaging Earthquakes

IUGG-1115

Recent developments of the ISC Seismic Event Bibliography

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The International Seismological Centre (ISC) is a not-for-profit organization operating in the UK for the last 50 years and producing the ISC Bulletin, which is regarded as the definitive worldwide summary of seismic events, both natural and anthropogenic

The aim of this service is to help researchers working in various fields of geoscience to gather extended information related to specific seismic events. To facilitate such task in 2012 we set up a database linking seismic events in the ISC Bulletin to bibliographic records of scientific articles (mostly peer-reviewed journals) that describe those events. Such association allows users of the ISC Event Bibliography to run searches (www.isc.ac.uk/event_bibliography/bibsearch.php) using a map-based web interface (e.g., global or specific area search) and, optionally, publication fields (e.g., specific journal, authors, year of the publication). Some of the most notable earthquakes are the subject of several hundreds of articles published over a period of few years. The journals included in our database are not limited to seismology but bring together a variety of geosciences fields (e.g., engineering seismology, geodesy and remote sensing, tectonophysics, monitoring research, tsunami, geology, geochemistry, hydrogeology, atmospheric sciences, etc.) making this service useful also in multidisciplinary studies. Usually papers dealing with large data set are not included (e.g., papers describing a seismic catalogue). Currently the ISC Event Bibliography includes over 17,000 individual publications from about 500 titles related to over 14,000 events that occurred in last 100+ years. The bibliographic records in the Event Bibliography start in the 1950s, and it is updated as new publications become available.

IASPEI (Seismology, Geophysics)

S03a - S03 Recent Large and Damaging Earthquakes

IUGG-1276

Lessons learnt from 2011 Sikkim earthquake – An engineers view

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An earthquake of M6.8 on Richter scale, which comes under the category of "Moderate Earthquake", hits the North Sikkim-Nepal border on September 18, 6.10PM (IST). It was widely felt in Sikkim, Assam, Meghalaya, Northern parts of West Bengal, Bihar, parts of other eastern and northern regions of India, including capital city Delhi. Wide scale shaking also reported from neighboring countries like Nepal, Tibet, Bhutan and Bangladesh. At least 78 people were killed in the earthquake. Landslides, rock falls, and mudslides were main responsible for most loss of life and damage to infrastructure and also related economic losses. It is seen that due to shaking, most multi-story reinforced concrete buildings, which were non-engineered structure sustained considerable damage. No doubt, in magnitude and scale of destruction, this might not be a landmark earthquake, but as per records available, there have been four earthquakes over magnitude eight in the Himalayas - 1897 Shillong, 1905 Kangra, 1934 Bihar-Nepal border and 1950 Arunachal Pradesh. So, the occurrence of a large magnitude earthquake cannot be ruled out.

In this paper an attempt has been made to highlight the lessons learnt from an engineer's point of view about Sikkim earthquake which may have done something that is likely to challenge the authorities to re-assess the country's building codes along with the relief issues of disaster mitigation and management in the inhospitable region of the Himalayas which is one of the most seismically active regions of the country. Also tried to study the social, economic and scientific impacts and other related disaster mitigation aspects with many valuable lessons learnt from this tragic event of the Sikkim earthquake of 18th September 2011.

IASPEI (Seismology, Geophysics)

S03b - S03 Recent Large and Damaging Earthquakes

IUGG-0270

Trending Discussion on Bihar-Nepal Earthquake (1934 & 1988) and its relation to Patna fault inferred from gravity and magnetic data

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Himalayan seismic belt is one of the most seismically active regions of the world resulting from the collision of Indo-Eurasian plates. Four great earthquakes, namely Shillong (1897), Kangra (1905), Bihar–Nepal (1934) and Assam–Tibet (1950), occurred during a short span of 53 years only. Out of these Bihar-Nepal earthquake of M 8.4 occurred on 15 January 1934 at around 2:13 PM (I.S.T.) (08:43 UTC) and caused widespread damage in the northern Bihar was one of the worst earthquakes in India's history. The epicenter was on the border between Nepal and the Indian state of Bihar. Quantitative interpretation of gravity and magnetic data give the good deal of information about the subsurface features of the Ganga basin. This basin is one of the major geological provinces of Indian subcontinent and attracted many scientists for its geological hazards. It is filled with sediments and alluvial deposits whose thickness increases from the Vindhyan exposures in the south to foothill of Himalayas in the north. At some places the thickness of sediments are over 6 km. The entire Himalayan range extending over 2500 km from west to east, and running parallel to it at its foothills at the Gangatic plains. The study reveals the thickening of granitic layer over Patna and surrounding regions and its projection in to the alluvium, restricting the extension of Patna fault further to Nepal. The Occurrence of 1934 (M8.4) and 1988 (M 6.5) are separate entities and not connected to Patna fault as the focal depth of these events were 60 and 70 Km, respectively. This suggests that the seismic activity is deep seated and probably may be associated with Main Boundary Fault (MFT). The seismic activity does not show its extension towards south suggesting the Patna fault to be in active.

IASPEI (Seismology, Geophysics)

S03b - S03 Recent Large and Damaging Earthquakes

IUGG-1103

Ludian earthquake (Aug.3,2014) and Jinggu earthquake (Oct.7,2014): comparison of strong ground motion, with implications for the disasters

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The M_S6.5 Ludian earthquake (27.1°N, 103.3°E; 12km depth) occurred on August 3, 2014, striking Ludian County of Yunnan Province, southwest China. The mainshock was characterized by strike-slip mechanism, with two nearly vertical nodal planes striking approximately NE and NW, respectively. The maximum intensity was IX (Chinese intensity scale), with the area above VI being 10,350 km^2. The seismic disaster caused 617 deaths, 112 missing, and 3,143 injuries. Months later, on October 7, 2014, there occurred the M_S6.6 Jinggu earthquake (23.4ºN, 100.5ºE; 11km depth), being similar to the Ludian earthquake in the perspective of earthquake parameters such as focal depth and magnitude. The maximum intensity was VIII, lower than the Ludian earthquake, with the area above VI being 11,930 km^2, larger than the Ludian earthquake. The disaster was much less, causing 1 death and 325 injuries, although the exposures of the two places in Yunnan are similar to each other. One of the questions is what is the cause of the sharp difference in the maximum intensity and earthquake fatality. Comparison of near-source strong motion data reveals that although the amplitudes of the two earthquakes at about 20s are comparable, which gave the similar M_S, 6.5 and 6.6, respectively, the high-frequency content of the Ludian earthquake is much higher than the Jinggu earthquake. For the Ludian earthquake, contribution to the high-frequency ground motion comes both from the high-frequency radiation of seismic waves and from the Doppler effect caused by the upward rupture propagation; the contribution to the disaster also comes from the topography and the landslides.

IASPEI (Seismology, Geophysics)

S03b - S03 Recent Large and Damaging Earthquakes

IUGG-1793

Bay of Bengal earthquake 21st May 2014, and strong ground motions

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The Mw 6.1, Bay of Bengal earthquake of 21 May 2014 was unusual, for its depth and was felt in a large area upto distances of 1600 km such as Delhi and Jaipur. This was an intraplate, strike-slip event, located far from the plate boundaries. The hypocentral depth is around 60 km which means the event occured in the oceanic mantle at a depth where generally the brittle rupture is not expected.As the Bay of Bengal earthquake did not occur in a subducting lithosphere, thermal shear-instability mechanism may explain theoccurrence of this event at depth of about 60-80 km. As the Bay of Bengal earthquake did not occur in a subducting lithosphere we may explain its occurrence by thermal shear instability mechanism or an alternative. The higher observed PGA values in the epicentral distance range of 530-2000 km are larger than continental or Himalayan arc earthquake, providing support for the perception that the felt area was unusually large. The higher PGA values may be due to the greater depth of the earthquake or high stress drop as observd for oceanic intraplate strike slip earthquakes. The larger PGA values at sites in Indo Gangetic plains in comparison to the shield sites shall also be discussed.

the Bay of Bengal earthquake did not occur in a subducting lithosphere, thermal shear-instability mechanism may explain theoccurrence of this event at depth of about 60-80 km.

IASPEI (Seismology, Geophysics)

S03b - S03 Recent Large and Damaging Earthquakes

IUGG-1814

The 2013 M=7 Lushan earthquake, the 2008 M=8 Wenchuan earthquake and the history earthquakes in the Bayan Har eastern region

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According to the seismic data of the telemeter seismographic network in Sichuan and the correlative historical information from internal and overseas, we research the historical seismicity along the Longmenshan, the Minjiang and the Huya faults in the eastern border area of the Bayan Har block. We analyze the distribution characteristics of aftershocks, the focal mechanism and the extended rupture along the Longmenshan fault zone of the 2008 M=8 Wenchuan earthquake and the 2013 M=7 Lushan earthquake. We discuss the features of energy release in the eastern border area of the Bayan Har block. Our results show that: ? We have identified a seismic gap of major earthquakes which exists in the south segment of the Longmenshan fault on the southwest of the M=7 Lushan earthquake. ? A short segment of energy possibly be released soon between the 2013 M=7 Lushan earthquake and the 2008 M=8 Wenchuan earthquake. ? The 2008 M=8 Wenchuan earthquake has caused that the energy released is sufficient in the middle segment of the Longmenshan fault. ? The energy release of the northern segment of the Longmenshan fault was triggered by the 2008 M=8 Wenchuan event and it is also enough. ? The historical earthquakes occurred along the Minjiang, the Huya and other faults in the eastern border area of the Bayan Har block leads to fairly extensive decomposition release of accumulated strain energy.

IASPEI (Seismology, Geophysics)

S03b - S03 Recent Large and Damaging Earthquakes

IUGG-2159

The Key Role of Eyewitnesses in Rapid Impact Assessment of Global Earthquakes

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Uncertainties in rapid assessment of global earthquakes' impact are intrinsically large. For small to moderate magnitude earthquakes, variations of epicentral location within uncertainties of real-time location estimates can lead to significant changes in impact scenario. An example is the 1999 M 5.9 Athens, Greece, earthquake located at about 18 km from the city center which caused 143 casualties. Undoubtedly, the death toll would have been significantly higher if, other things being equal, the epicentre had been closer to the city by 5 or 10 km. For large magnitude earthquakes, fault rupture parameters which are unknown or only partially determined in the immediate aftermath of an earthquake occurrence play an important role in the spatial distribution of damage.

We present the strategy and methods implemented at the European-Mediterranean Seismological Centre (EMSC) for rapidly collecting in-situ observations on earthquake effects from eyewitnesses to better constrain rapid impact assessment of global earthquakes. We show how Internet and communication technologies are creating new potential for rapid and massive public involvement by both active and passive means. We underline the importance of merging results from different methods to improve performance and reliability. We explore the impact of the pervasive use of smartphones and the potential roles of networked devices. Finally, we discuss how these approaches not only augment data collection on earthquake phenomenon at little cost but also how they change the way that we, as scientists, interface with eyewitnesses and how it pushes us to better understand and respond to the public's demands and expectations in the immediate aftermath of earthquakes.

IASPEI (Seismology, Geophysics)

S03b - S03 Recent Large and Damaging Earthquakes

IUGG-5171

Source Parameters of the Mw=7.8 Ghosht- Iran Earthquake

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The strong Mw = 7.8 earthquake occurred on 16 April 2013 felted in south-east Iran, Persian Gulf states and south-western cities of Asia. It was located near Ghosht in Iran that is characterized as low populated mountain and range region. The event was followed by a medium sized Mw = 5.7 aftershock on 17 April 2013. The shakings left several causalities in Pakistan and destructions in Iran and Pakistan. The region is under the multiple convergences between the Persian Gulf, Indian and Eurasian plates. Based on the seismicity distribution there exist a crustal seismic activity band (above 50 km depth) near Makran coasts and an under crustal band (between 50 km and 150 km) including a gap of seismicity between Makran and the rest of the Persian Plateau. After dislocation grid search the best-fitted double couple showed: strike 75, dip 35, rake 75 and Mw = 7.66 for the mainshock and strike 80, dip 40, rake 90 and Mw = 5.53 for the mentioned aftershock. According to the deviatoric inversion results there exist 39% of CLVD for the mainshock and 5% of CLVD for the same aftershock.

IASPEI (Seismology, Geophysics)

S03p - S03 Recent Large and Damaging Earthquakes

S03p-519

Co-seismic effects of 2010 Maule earthquake considering Earth's curvature and layered structure

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The 2010 Chile Maule earthquake ranks as the sixth largest earthquake ever to be recorded by a seismograph. Plane assumption is inapplicability to the exceptionally large earthquakes, in this paper, with the finite element method considering Earth's layered structure and curvature, co-seismic deformation field and stress field are calculated. Based on the Coulomb stress change, seismic activity of surrounding faults and triggering of aftershocks is estimated. The results show that: the effects of Earth's layered structure and curvature on co-seismic horizontal and vertical displacement are significant, neglecting curvature effects may produce exaggeration (2 times) of strain and lead to overestimate of near-field seismic activity. The range of influence of co-seismic displacement is about thousands of kilometers, relatively large horizontal displacements locate on the northwest and southeast of the seismic fault. Horizontal displacement in One-half of South America is about the magnitude order of 0.5 mm. Stress drop caused by this earthquake in Central Argentina is equivalent to 5-10 years tectonic stress accumulation while in Northern Argentina and Southern Argentina is equivalent to 1-5 years tectonic stress release. Coulomb stress change on optimally orientated faults are calculated, 66.2% of aftershocks occur in regions where the failure stress exceed 10 kPa. The great Mw 6.9 and Mw 7.0 aftershocks near Pichilemu were triggered by the great Maule earthquake.

IASPEI (Seismology, Geophysics)

S03p - S03 Recent Large and Damaging Earthquakes

S03p-520

How the 2013 Lushan earthquake (Ms=7.0) triggered its aftershocks: Insights from static Coulomb stress change calculations

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The Lushan earthquake Ms7.0 occurred at 08:02 Beijing Time (00:02 UTC) on April 20, 2013, located on the eastern margin of the Tibetan Plateau, where 2008 Ms8.0 Wenchuan earthquake took place. It is the other strong shock following the Wenchuan earthquake occurred on the Longmen Shan thrust fault. A large number of aftershocks were recorded after the main shock. To investigate how the aftershocks are triggered, we firstly relocate the 6-month aftershock sequence by double-difference algorithm. Next, we calculate Coulomb failure stress changes imparted by the Lushan main shock both on the optimally oriented plane and on the aftershock nodal planes. Then we examine the correspondence between the Coulomb failure stress changes and the spatial distribution of the aftershocks. The computed results show that most of the aftershock hypocenters did not occur on the region with the positive Coulomb stress changes caused by the Lushan main shock. Moreover, the majority of aftershock nodal planes were brought away from failure by coseismic Coulomb stresses. This implies coseismic static Coulomb stress changes may not be the governing process for aftershock genesis. In contrast, postseismic stress transfer by processes of afterslip and pore fluid flow are assumed to play an important part in aftershock triggering based upon the spatiotemporal distribution of the aftershocks.

IASPEI (Seismology, Geophysics)

S03p - S03 Recent Large and Damaging Earthquakes

S03p-521

Acceleration of seismicity in intraplate stress shadows

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Megathrusts produce large permanent lithospheric displacements as well as strong transient ground shaking up to regional distances. The lateral permanent displacements construct stress shadows over a wide backarc region. The Korean Peninsula is placed in the far-eastern Eurasian plate that belongs to a stable intraplate region with a low earthquake occurrence rate and diffused seismicity, and is located in the backarc at ~1300 km in the west from the epicenter of the 11 March 2011 M9.0 Tohoku-Oki earthquake. The seismicity around the Korean Peninsula was increased significantly after the megathrust, which is not consistent with the expected seismic-quiescence. Strong seismic waves cause large dynamic stress changes, incurring fluid migration and increasing pore fluid pressure in the media. The lithospheric displacements directing to the epicenter on the convergent plate boundary develop transient radial tension field over the backarc lithospheres, which is subparallel with the preseismic ambient compressional field. The pore pressure growth and radial tension field decrease the Coulomb failure stress, increasing episodic increases of seismicity in both fault zones and intact media. The ambient stress field is recovered gradually as the induced stress field diminishes with time by tectonic loading. The seismicity changes with the temporal evolution of stress field. A series of moderate-size earthquakes and earthquake swarms occur as a consequence of medium response to the temporal evolution of stress field. The long-term evolution of seismicity is expected to continue until the preseismic ambient stress field is fully recovered.

IASPEI (Seismology, Geophysics)

S03p - S03 Recent Large and Damaging Earthquakes

S03p-522

Correlation between Coulomb stress imparted by the 2011 Tohoku-Oki earthquake and seismicity rate change in Kanto, Japan

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We studied the seismicity rate increase in the Kanto region around Tokyo following the 2011 Tohoku-Oki earthquake (Mw9.0) and showed that this was well correlated with the static increases in the Coulomb failure function (ΔCFF) transferred from the Tohoku-Oki earthquake sequence. Because earthquakes in the Kanto region exhibit various focal mechanisms, the receiver faults for the ΔCFF were assumed to be reliable focal mechanisms for ~3,000 earthquakes compiled from three networks (F-net, JMA network, and MeSO-net).

The histograms of ΔCFF showed that more events in the postseismic period had positive ΔCFF values than did those in the preseismic period. Among the 928 receiver faults showing the significant ΔCFF with absolute values ≥ 0.1 bars in the preseismic period, 717 receiver faults (77.3 %) indicated positive ΔCFF. However, 1,334 (88.2 %) out of 1,513 receiver faults indicated positive ΔCFF in the postseismic period. This temporal change was proven to be statistically significant by using a Monte Carlo method with bootstrap resampling.

Earthquakes of focal mechanisms with positive ΔCFF values drastically increased, while those with negative ΔCFFs showed no obvious changes except for immediately after the mainshock. This fault-dependent seismicity change strongly supports the contribution of the Coulomb stress transferred from the Tohoku-Oki sequence to the seismicity rate change in the Kanto region. Immediately following the mainshock, earthquakes of all types of focal mechanisms were activated, but the increased seismicity rate of earthquakes of focal mechanisms with negative ΔCFFs

returned to the background level within a few months. This suggests that there might be other contributing factors such as dynamic stress triggering.

IASPEI (Seismology, Geophysics)

S03p - S03 Recent Large and Damaging Earthquakes

S03p-523

Overview of seismicity changes inland Japan after the 2011 Tohoku-Oki earthquake and its interpretation

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This paper overviews the widespread changes in seismicity rate and distribution of focal mechanism after the Tohoku-Oki earthquake (Mw9.0) and summarize the possible contributing factors. In Tohoku, westward from the Tohoku-Oki source, significant increases in seismicity rate were observed in N. and S. Akita, SW off Oga peninsula, and Yamagata/Fukushima and Ibaraki/Fukushima boundary regions as well as other scattered areas. However, aftershock activities in the source regions of recent large earthquakes such as the 2008 Iwate-Miyagi earthquake have been suppressed. In Kanto, southwest of the Tohoku-Oki source, interplate earthquakes were typically activated, while belt-like seismicity along the western edge of slab-slab contact zone and shallow earthquakes in some areas were also activated.

The most plausible factor is the static changes in the Coulomb stress, which seems to be valid for retrospectively forecasting the changes in seismicity on some level, while some activated seismicity showed clear counter-evidence. Remotely triggered local events, whose origin times are well coincided with the arrivals of mainshock seismic waves, suggest that dynamic stress changes also contribute. Some swarm-like activities, showing temporal expansion of the focal area which is attributed to fluid diffusion, suggest that changes in pore fluid pressure should be another possible factor. The contribution of indirectly triggered earthquakes might be important in some regions because stress changes imparted by neighboring indirect aftershocks could be comparable with those from a distant mainshock. Postseisimc slip and viscoelastic effect would play an important role for long-term hazard assessments.

IASPEI (Seismology, Geophysics)

S04a - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-0261

Monitoring of the strength-stress-strain state for earthquake forecast

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Crustal earthquakes are the result of very slow tectonic movements which are forming the geological structures and leading to the accumulation of the considerable elastic energy which is discharged into the environment as a result of the destruction of the rocks in the places where tectonic stresses reach the strength limit. Therefore, earthquake prediction should be based on the analysis of the strength-stress-strain state of the earth's crust of the studied area. For this we need to elaborate create the geomechanical model of the studied crustal region using geological, geophysical and geodetic information. Firstly we should take into account the fault-block structure of the crust as genetically related to plate tectonics and seismic processes. Further we should monitor the changes in of the stress-strain state and in strength values. Since each earthquake is the elementary damage it can be used to detect changes in the elastic and strength parameters of the model and the associated incremental stresses and strains. As a result we can identify areas where crustal energy saturations are increased and the stress level approaches to the strength limit. Abnormal changes of these parameters as shown by monitoring the stress state of the Southern California during 2009-2014 years preceded by the four strong earthquakes with M = 5.6-7.2 for the week before the events. It should be noted that such latter increases (only one week before the event) hardly can be connected only with the stress change (because of very low tectonic velocities resulting in the stress change), and the considerable change in strength limits should be suggested also.

IASPEI (Seismology, Geophysics)

S04a - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-0418

Dynamic rupture in damage-breakage rheology model including rock dilation and isotropic radiation

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A number of recent studies found evidence for isotropic components and enhanced P radiation generated by tectonic [e.g., Castro and Ben-Zion 2013; Ross et al. 2015] and mining-induced [e.g. Kwiatek and Ben-Zion 2013] earthquakes. Co-seismic changes of elastic moduli in source volumes are predicted to produce 'damage-related-radiation' that can have an appreciable isotropic component [Ben-Zion and Ampuero, 2009]. While the overall source is still dominated by deviatoric deformation, a small isotropic component can lead to dynamic changes of normal stresses at the source region that can have significant effects on many aspects of the local physics. Lyakhovsky and Ben-Zion recently combined a thermodynamically-based continuum damage rheology with continuum breakage mechanics for granular flow within active slip zones. The continuum damage-breakage rheology model provides a physical basis for analyzing dynamic rupture processes as a phase transition between solid and granular states during the occurrence of ruptures. The dynamic accumulation of damage near the rupture front, transition to the granular phase within the slipping zone, and stress relaxation are expected to be accompanied by significant volumetric effects and dynamic changes of normal stress. Numerical simulations of dynamic ruptures in a medium governed by the continuum damage-breakage rheology model corroborate these expectations. The initiation of dynamic shear rupture in the model is preceded by a 'nucleation process' associated with dilation. The propagation of rupture front and slip accumulation at a point are correlated with sharp dynamic dilation followed by a gradual decay to a level associated with the final volumetric change associated with the granular phase transition in the slipping zone.

IASPEI (Seismology, Geophysics)

S04a - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-1734

Fault slip simulation using a spring-block model with a rate- and-state friction law

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The deformation of a composite fault zone, consisting of a some number of segments with different rheology and different frictional properties is considered. Numerical simulations of composite fault slip cycles are conducted using a two-degree-of-freedom spring-block model with a rate- and state-friction law at the contact with fixed base. By varying the model parameters for each block, various slip patterns are obtained, including stick-slip, “slow earthquakes”, slow slip events and aseismic creep.
The numerical code allows to simulate a system consisting of an arbitrary number of blocks connected to each other and to the plate moving at a constant velocity by elastic springs. We consider the system of connected blocks with different properties at contacts with the base as the segment of a tectonic fault. This allows us to explore the laws of different deformation mode origin and propagation along the fault.
The simulations show that the number and arrangement of blocks showing stick-slip (locked sections or «asperities») define both the value of radiated energy and its distribution in time. Under certain conditions the dynamic instability that occurred at a local section, can spread to rather extensive areas, involving sections of aseismic slip in dynamic movement, and, therefore, in the process of seismic waves radiation. At the same time, sections of stable creep and slow slip events, in their turn, affect formation of dynamic failures, triggering them.
The effect of arrangement of fault sections with different rheologies on fault deformation mode, on integral value of 'radiated' energy, on statistics and spatial distribution of the dynamic and slow slip events along the fault and on recurrence time is investigated.

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IASPEI (Seismology, Geophysics)

S04a - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-1915

Synchronous Quantum Processes in Continuum with Shear and Rotation Strains

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The synchronous processes could influence the different radiation processes on the quantum level. The synchronous quantum processes appear in all radiation processes as basic phenomena in the world, but here we consider only those synchronous processes which appear due to the deformations by shear and rotation stresses and relate to the Planck black body radiation.

Here, we try to use the basic elements of quantum theory for the synchronous processes, which relate to the fracture and to the lightning and aurora events. Thus, we consider the influence of the given stresses on the quantum processes formed in a synchronous system. We follow the Asymmetric Continuum with the shear and rotation strains; additionally we consider the doublet continuum with the elastic and time-rate plastic strains; in this way we try to describe formation of the fracture processes and waves in solids. The considered theory includes also the fluid part with the flow processes in liquid and gas due to the molecular strains.

IASPEI (Seismology, Geophysics)

S04a - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-3334

Reinvestigation of the coulomb failure model: Its modeling foundation and performance testing for the earthquake stress triggering

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Over the past more than twenty years, the underlying physical mechanisms of earthquakes have been comprehensively investigated using the Coulomb stress change, referring to studying the roles of stress transfer among earthquakes and fault networks. Based on the Coulomb failure model, although there have had numerous retrospective studies for the Coulomb stress triggering, only a few successful prospective studies have been exhibited, and many retrospective studies were failed to pass through prospective test. To resolve the failure of the Coulomb stress model that it cannot interpret the spatiotemporal pattern of aftershocks remarkably well in many cases, almost all studies have been rested on the common Coulomb failure model. However, relatively little attention has been paid to the investigation of the Coulomb failure model itself. In this work, we reinvestigate this problem using the case studies for the 2008 Wenchuan (Mw 7.9) and the 2002 Denali (Mw 7.9) earthquakes. We find that: (1) using optimally oriented planes (OOPs) with the consideration of their uncertainties improves the consistency between Coulomb stress maps and aftershocks, (2) the OOPs are not consistent with the focal mechanisms of larger aftershocks, (3) invariants of stress tensors and coseismic gravity changes induced by the two mainshocks can interpret their aftershock-patterns as well. Considering that there are still inherent uncertainties in the parameters of the Coulomb failure model such as receiver faults, friction and Skempton's coefficients, it is suggested to use the invariants of stress tensors and coseismic gravity changes as complementary quantitative indices for operational earthquake prediction.

IASPEI (Seismology, Geophysics)

S04b - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-1577

Fracturing of pre-stressed water saturated sandstone samples by pore-pressure changes

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We investigated the spatio-temporal distribution of acoustic emission activity in water saturated pre-stressed Flechtingen sandstone samples. The samples were brought close to failure by application of axial load additional to confining pressure. Water was then injected in several consecutive cycles at the bottom end of the samples, leading to acoustic emission activity.

For our analysis we assumed that acoustic events are triggered by the pore pressure increase i.e. the Mohr-Coulomb failure condition is reached by decrease of the effective stress. Pore pressure changes in the sample were estimated by means of an analytical solution of the 1D diffusion equation.

The interpretation of the spatio-temporal distribution of both the acoustic events and the pore pressure suggests that in the earlier stage of the experiments micro fractures on grain scale are successively triggered by the migration of critical pore pressure levels through the sample. Hereby the onset level for acoustic emission activity is controlled by the applied pore pressure of the previous cycle according an apparent Kaiser effect in terms of pore pressure. This memory effect of the rock is not observed if additional axial stress is applied to the sample before the next injection cycle.

Moreover the behaviour of a highly fractured rock in the final stage of the failure experiments differs from the previous loading cycles. Here the final formation of a macroscopic fault is observed: although it is likely triggered by pore pressure, the densest part of the acoustic emission activity is controlled by interaction of pre-existing micro fractures and rapidly increasing localized damage rather than by propagation of a pore pressure pulse.

IASPEI (Seismology, Geophysics)

S04b - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-3948

The impact of geology on the nucleation of 2009 L'Aquila earthquake via 3D numerical optimization model of ground deformation pattern

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To investigate the impact of the deep fault geometry and tectonic setting on the co-seismic ground deformation pattern of April 6, 2009 L'Aquila earthquake (Mw 6.3, Central Italy), we include the 3D structural-geological model, built for the study area, in a Finite Element Environment.
To this purpose, we model the evolution of the failure processes in a structural mechanical context, under the plane stress approximation. We assume the linear elastic behavior of the involved materials and evolve our numerical model through two stages: (i) compacting under the weight of the rock successions (gravity loading), the deformation model reaches a stable equilibrium; (ii) the co-seismic stage simulates, through a distributed slip along the active fault, the released stresses. In the second step, in order to individuate the seismogenic fault, we analyze the spatial distribution of the fore- and aftershocks in the considered area.
In the optimization procedure, based on the genetic algorithm, we exploit the DInSAR deformation velocity maps retrieved by ENVISAT (ascending and descending orbits) and COSMO-SkyMed data (ascending orbit) to constrain the numerical solution; more specifically, we first generate several forward mechanical models, then, we compare these with the recorded ground deformation fields, in order to select the best boundaries setting.
Finally, the performed multi-parametric 3D numeric model allow us to quantify the stress-drop associated to the L'Aquila seismic event.

IASPEI (Seismology, Geophysics)

S04b - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-4203

Coseismic stress evolution along the Mexican subduction zone: Comparison among inverted and theoretical slip distributions from recent large subduction earthquakes.

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In the Mexican Subduction Zone, the Rivera and Cocos oceanic plates subducts beneath the continental North American plate. Here we analyze the coseismic stress change evolution produced by 14 recent large subduction earthquakes ($M \geq 6.9$), occurred between 1973 and 2014 along the Mexican Subduction zone. Two of the analyzed earthquakes occurred along the tectonic interface between the Rivera and North American plates, and the other 12 earthquakes ruptured along the Cocos - North American plate interface. Coseismic stress changes are computed based on the slip distribution of the studied earthquakes, obtained from two different ways. On one hand, the stress changes (ΔCFS_T) are calculated assuming a theoretical semi-elliptical slip distribution on the fault plane, smoothed in the two spatial directions by means of a 2D cosine taper. This assumed distribution yields an approximately constant stress drop inside the rupture area. On the other hand, we compute for the same 14 earthquakes analyzed the stress changes (ΔCFS_I) based on slip distributions obtained from waveform inversions. Stress changes are calculated along the extended fault plane corresponding to the tectonic interface. Results obtained from both methodologies are then compared in terms of their spatio-temporal evolution. The tectonic loading along the extended fault plane is taken into account by back-slip modeling, based on the known convergent slip rates along the corresponding subduction tectonic interfaces.

IASPEI (Seismology, Geophysics)

S04b - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-4439

Analysis of two-parameters rate-and-state equation for different critical stresses by Grassberger-Procaccia method

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A problem of seismic activity change due to human action is considered. The widely used “stick-slip” model of the seismic regime with “rate-and-state' friction law was used to describe a tectonic fault sliding. The main distinctions of used model from the common one are the followings: we consider two-parameters type of the friction law and we vary the value of critical shear stress in the rate-and-state equation in suggestion that this is the value varied by human impact (by mining, fluid injection and production and so on). Calculations were done for the critical stress varied from 5MPa up to 50 MPa. For each value of the critical stress, the time series of the displacement along the fault, its rate and shear stress were calculated. The results were analyzed with the help of Grassberger-Procaccia method of correlation integral calculation for different embedding space dimensions.

It was found that if the critical stress increase, the system behavior changes significantly. An estimation of the correlation dimensions showed, that an increase of the critical stresses results in increase of the correlation dimensionality. It was found, that if the critical stress continue to increase, the correlation dimension would stop to increase. A comparison of the obtained results with real induced seismicity data showed that in real case the correlation dimensionality is higher. This distinguish can be explained by taking into account the presence of the seismic events, which are not related with human influence and which can be considered as a stochastic background. An addition of random component with signal/noise ratio 2 to the model data resulted in increase of the model correlation dimensionality to 4-5, which is in good correspondence with studied induced seismicity data.

IASPEI (Seismology, Geophysics)

S04b - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-4807

2D fully dynamic SEM earthquake cycle simulation for in-plane shear fault

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Earthquake cycle simulations (ECSs) based on rate-and-state friction laws have been performed to reproduce historical earthquake occurrences, aiming at understanding the earthquake generation mechanisms and forecasting the future earthquakes. Many previous numerical models have assumed a homogeneous elastic half-space medium and used quasi-dynamic BIEM (boundary-integral-equation-method) approaches introducing the radiation damping to approximate the inertial term (Rice, 1993).

Recently, Kaneko et al. (2011) have employed a SEM (spectral-element-method) approach, which enables us to consider heterogeneous material properties, and performed 2D fully dynamic earthquake cycle simulations for anti-plane faults. Aiming at simulating interplate earthquake cycles at subduction zones, we extend their study to simulations for in-plane faults and implement our numerical scheme in a dynamic rupture SEM code (Ampuero, 2002). In case of in-plane fault, we explicitly calculate the fault-normal displacements during earthquake cycles, which do not appear in case of anti-plane fault. Note that the fault-normal displacements have not explicitly been calculated in most of BIEM ECSs. We validate our approach by comparing the cases of anti-plane and in-plane faults and obtain approximately the same recurrence times for two cases where the same nucleation sizes are obtained by adjusting frictional parameters. The code also works well for a vertically dipping fault in an elastic half-space. For dipping fault rupture such as the 2011 Tohoku earthquake in a homogeneous elastic half-space medium, we successfully simulate scenarios of single dynamic rupture propagation. At present, however, we have problems in simulating quasi-dynamic interseismic simulations for this case.

IASPEI (Seismology, Geophysics)

S04b - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-5149

Estimation of Interseismic Coupling at subduction zones using a Slab Model

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The interseismic coupling is related to seismic loading processes, and therefore important for earthquake hazard assessment. For subduction zones, we propose an approach to determine this value based on a Slab Model, which is different to the standard Back-Slip Model suggested by Savage in 1983. The main feature of this model is to consider slip on both interfaces of the slab as it subducts. Along each interface, we assume the slip rate to be a smooth function varying from locked or no-slip zones to free-slip zones. The crustal displacement rate calculated from this model is due to the contribution from slip on both interfaces. Considering the geometry of subduction as known from seismicity studies, and prescribing the slip rate at the free-slip zones, we invert from the observed crustal displacement rate the slip rate at locked zones, and thus obtain the interseismic coupling. The spatial variability of interseismic coupling depends on a variety of factors, but mainly on the width of the transition zones within the upper interface of the subducting slab. This model is physically reasonable in contrast to the Back-Slip Model, because in the latter model, slip occurs in a brittle regime in the opposite direction to the loading process, which is not reasonable. We show that for the Chile subduction zone, high coupling relates to large widths of the locked zone, therefore are capable of larger coseismic slip. The interpretation of the interseismic coupling based on the Slab Model is very different to the one based on the Back-Slip Model.

IASPEI (Seismology, Geophysics)

S04c - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-0715

Revealing the space region of a fracture nucleation site prior to its formation

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Analysis of laboratory experiments on deformation of rocks and in-situ measurements has shown that the process of defect accumulation is divided in two stages. At the first stage, defects are generated chaotically and have a specific size determined by the typical structural element of a material (for example, a grain in the granite or interpore bridges in the sandstone). These defects do not grow. The second stage exhibits generation of defects of various sizes independent of structure. Interaction between them results in arising of “dangerous defects” which are capable of self-development. We sagest that the “dangerous defects” give rise to the fracture nucleation site. This model of fracture has been deduced from experimental methods such as X-ray micro tomography and acoustic emission.

These two stages can be distinguished by the function of energy distribution of acoustic emission signals. At the first stage the distribution is approximated by the exponential function while the second stage features the power-law function which indicates the self-organized criticality state.

With this approach, we can determine co-ordinates of a fracture nucleation site prior to its formation.

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IASPEI (Seismology, Geophysics)

S04c - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-1100

Generation mechanism of slow earthquakes: effects of dehydration reaction coupled with slip-induced dilatancy

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We study theoretically why slow earthquakes occur more commonly at hot subduction zones. We try to understand the generation mechanism of slow earthquakes comprehensively assuming two end member models for subduction zone, that is, ideally hot and cold subduction zones. A focus is put on slip phenomena occurring at the down-dip edge of seismic coupling region. We take account of mineral dehydration coupled with slip-induced dilatancy in the modeling under the assumption of high-pressure fluid. In fact, mineral equilibria calculations seem to point towards a potential role played by mineral dehydrations (Fagereng and Diener 2011). Such reactions are expected to occur at the down dip edge of seismic coupling region in hot subductions zone such as at Shikoku and Cascadia. We employ the fault rupture model developed by Suzuki and Yamashita (2009, 2010), which includes thermoporoelastic effects, slip-induced dilatancy and inertia term, coupling it with Brantut et al (2010) formulation of thermo-chemical pore fluid pressurization. Our analysis shows that slow slip events (SSEs) will be modeled if the dehydration reaction is coupled with slip-induced dilatancy. Considerable slip-induced dilatancy is, in fact, expected to occur at the down-dip edge of seismic coupling region in hot subduction zones because of repetitive fault rock fracturing due to dehydration reaction. At cold subduction zone, dehydration reactions are not expected at the down-dip edge of seismic coupling region, so that sufficient slip-induced dilatancy will not occur there. This suppresses the occurrence of slow earthquakes at cold subduction zones.

IASPEI (Seismology, Geophysics)

S04c - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-2367

The Pattern of Acoustic Emission under Fluid Initiation of Failure from Laboratory Experiment

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The results of the laboratory experiment on the initiation of acoustic emission in a loaded specimen by wetting a part of its surface without a considerable increase in the pore pressure are analyzed. The experiment was conducted on the lever press in the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences. Infusion of water into the surface of the specimen initiated the swarm acoustic emission, which, after having migrated to the area with higher stresses, culminated in the formation of a macrofracture. The analysis revealed the regularities in the excitation and relaxation of the acoustic activity in response to the different types of the initiation:

- the “forced” excitation by stepwise increasing the load at the initial stage of the experiment;

- excitation resulting from fluid diffusion, which can be associated with the reduction in the material strength due to wetting;

- excitation that reflects the preparation for the emergence of a macrofracture in the area with the highest Coulomb stresses;

- spontaneous excitation of swarm activity at the stage of relaxation of the acoustic emission after the formation of macrofracture.

The features revealed in the acoustic time series at the stages of excitation and decay of the emission are qualitatively similar to the trends identified in the variations of seismic parameters during the natural swarms, preparation of the sources of the strong earthquakes, and relaxation of the aftershocks. In particular,

the obtained results support the hypothesis of fluid initiation of non-volcanic seismic swarms.

IASPEI (Seismology, Geophysics)

S04c - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-2668

Cross–disciplinary observation of pre-earthquake signals and their validation. The LAIC approach.

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One of the most discussed recently topics is the coupling mechanism which generates anomalies in different near-Earth shells starting from boundary layer of atmosphere up to magnetosphere of our planet, which was generalized in the form of the Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) model. We use multi-instrument space-borne observations and detail analysis of key processes in atmosphere, which modify the Earth plasma environment system under various geophysical conditions including major earthquake events. Our approach is based on a joint analysis of several physical and environmental parameters (satellite thermal infrared radiation (STIR), electron concentration in the ionosphere (GPS/TEC), radon/ion activities and air temperature) that were found to be associated with earthquake processes. The science rationale for multidisciplinary analysis is based on the LAIC concept (Pulinets and Ouzounov, 2011), which explains the synergy of different physical processes and anomalous variations, usually named short-term pre-earthquake anomalies. In 2012 (Pre-Earthquake project, EU FP7) we started joint observations over several testing regions including California, Japan, Taiwan and Kamchatka. In 2013 as part of LAIC validation, we started retrospective/prospective analysis of pre-earthquake signals (LAIC project, ISSI-Bern). Our initial results from retrospective/prospective testing show the presence of anomalies in the atmosphere and ionosphere before most of the significant (M>6) earthquakes (2013-2014). Our findings suggest that physically based pre-earthquake signals provide a short-term predictive power and important feedback needed to improve/correct our understanding of the physical processes during earthquake preparation phases.

IASPEI (Seismology, Geophysics)

S04c - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-2746

Voids strengthen rock friction at subseismic slip velocity: A microscopic view of dilatancy effects

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It has been considered that friction depends on the real contact area between surfaces. But, when the interfaces slide very fast ($>10^{-3}$m/s), we found that voids between the sliding surfaces play an important role for high slip rate friction. During the rock-rock friction experiments of gabbro at sub-seismic slip rate ($\sim10^{-3}$m/s), friction does not reach steady state but fluctuates within certain range. The amplitudes of compressional waves transmitted across the slipping interfaces decrease when sliding friction becomes high and vice versa. This variation can be interpreted based on the scattering theory; high friction is caused by the creation of large-scale voids and low friction state is achieved by grain size reduction caused by a comminution process. Such interpretation was confirmed by the experiments with a synthetic gouge layer. The result can be interpreted as an extension of force chain theory to high velocity sliding regime. And this mechanism could be a microscopic aspect of dilatancy process.

IASPEI (Seismology, Geophysics)

S04c - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-5366

Seasonal modulation of seismicity: The competing/collaborative effect of snow and ice load

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Tectonic forces responsible for mountain building must overcome, among others, gravity; this suggests the possibility for competing effects of tectonic forces and the load due to snow and ice cover. Compared to other seasonal meteorological phenomena (e.g. rainfall), snow and ice load are characterized by a longer residence time and a relatively more homogeneous distribution over the Earth surface. As evidenced by theoretical computations and quantitative analyses of seismicity, they may perturb the stress pattern within the entire crust and possibly deeper.

Seasonal patterns associated with stress modulation and earthquake occurrence have been detected in regions characterized by present day mountain building and glacial retreat in the Northern Hemisphere. In the Himalaya and the Alps the seismicity is peaking in spring and summer; opposite behavior - peak in fall and winter - is observed in the Apennines. This diametral behavior well correlates with the dominant tectonic regime: peak in spring and summer in contractional areas, peak in fall and winter in tensional areas. In this study the analysis of the seasonal effect is extended to several contractional (e.g. Zagros and Caucasus) and extensional regions; counter-examples, from regions where no seasonal modulation is expected (e.g. Tropical Atlantic Ridge), are considered as well. In the Southern Hemisphere, a quantitative study is warranted only in Antarctica, where the Circum-Antarctic ridge, as a whole, reacts to the seasonal thaw on the continent.

Our findings generalize to different seismotectonic settings the observations made about short-term (seasonal) and long-term (secular) modulation of seismicity, and confirm that snow and ice thaw may cause crustal deformations that modulate seismicity.

IASPEI (Seismology, Geophysics)

S04d - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-0493

On new properties of aftershock's flow of the strong earthquakes

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This report describes two previously unknown properties of the flow of earthquakes. The first property is that the strongest aftershock of strong earthquake can be induced by seismic circumnavigation echo - surface seismic waves that made the revolution around the Earth and returning in the epicentral area of the main shock after 200 min. The observed phenomenon increase the probability of a specific scenario of seismic process in the epicentral area of strong earthquake occurred. The second property is the modulation of the activity of aftershocks spheroidal oscillations of the Earth, excited the main shock of the earthquake. The work was partly supported by the Russian Foundation for Basic Research (grants 12-05-00799, 13-05-00066 and 15-05-00491).

IASPEI (Seismology, Geophysics)

S04d - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-0541

The emergence of coherent oscillations after the earthquakes

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The records from the wideband IRIS seismic stations located in different regions of the world are analyzed. The phenomenon of emergence of regional- and global-scale coherent oscillations after the earthquakes with M ≥ 7 is revealed. Coherence emerges irrespective of the epicentral location and source depth of the parental earthquake; it neither depends on the location of the receiving stations. The effect is most clearly pronounced at the periods of the oscillations ranging from 5 to 10 min. Coherence is detected at earliest 3.1 h after the parent earthquake and lasts for one to a few days, depending on the magnitude of the event. In the earthquakes with M ≥ 7 that occurred in the world during the studied period (from January 1, 2000 to March 11, 2011), an increase is revealed in the number of the repeated quakes within three days after the preceding event. This increase coincides with the periods of occurrence of the coherent oscillations and probably points to the influence of these oscillations on the potential sources of the earthquakes, which are at the metastable state. The results suggest a long-range interaction of the earthquakes as a probable cause of this phenomenon.

IASPEI (Seismology, Geophysics)

S04d - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-1774

Exploring aftershock properties to study stress magnitudes and frictional conditions

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Stress magnitudes and frictional faulting properties vary with depth and may strongly affect earthquake statistics. Nevertheless, if the Anderson faulting theory may be used to define the relative stress magnitudes, it remains extremely difficult to observe significant variations of earthquake properties from the top to the bottom of the seismogenic layer.

Here, we concentrate on aftershock sequences in strike-slip faulting regimes to isolate specific temporal properties of this major relaxation process with respect to depth. We consider the major strike-slip faults in California, alone and all together. We find very clear and stable dependence on depth of the duration of the early stage of aftershock activity that does not fit with the power-law regime (c-value in the Omori-Utsu law). At depths from 5 to about 15 km the logarithm of c-value demonstrates linear decay with increasing depth. We show that this gradient may be numerically converted to the values of friction coefficient. We discuss an opposite dependence on depth in a range from 0 to 5 km which is particularly clear for the seismicity in zones of geothermal fields (Geysers, Salton Sea, Mammoth Lakes). We show that the analysis of the c-value of the Omori-Utsu law for the aftershock decay rates in our specific task may be replaced by a non-parametric analysis of the aftershock times relative to the moments of the main shocks. We demonstrate that the logarithm of geometric average of times, normalised with the geometric average of the beginning and of the end of the considered interval, strongly correlates with the c-value estimates at a condition of the fixed p-value.
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IASPEI (Seismology, Geophysics)

S04d - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-3479

Dynamically triggered regional seismicity by 2014 Ms7.3 Yutian Earthquake, Xinjiang

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There occurred Ms7.3 Yutian earthquake on Feb.12, 2014, in Yutian county , Xinjiang. Most of its aftershocks locate in the southwest of Ms7.3 earthquake epicenter, and distribute in the range of 49km, but small earthquakes are active in two region, which is respectively about 25km in the northeast of the Ms7.3 earthquake epicenter and 45km in the north. In addition, the seismicity rate of the Ms≥1.4 earthquakes in Kuche region, the Ms≥2.8 earthquakes in Keping block and the Ms≥2.1 earthquakes in Jiashi region, where are about 600km from the Ms7.3 earthquake epicenter, increase sharply after Ms7.3 earthquake.

Based on the discrete wavenumber method, we investigate the dynamic Coulomb stress change produced by the fault rupture of Ms7.3Yutian earthquake, on five points in the above regions, and discuss the dynamically triggered regional seismicity. The result shows that the peak values of dynamic Coulomb stress change of the points in the northeastern part and the northern one are respectively 0.96Mpa and 0.38Mpa, which are higher than dynamic triggering threshold 0.1Mpa; the peak values of the points in Kuche region, Keping block and Jiashi region are respectively 0.1Mpa,0.06Mpa and 0.1Mpa, which is near to the threshold. It indicates that the dynamic Coulomb stress change produced by Ms7.3Yutian earthquake encouraged small earthquake activity in the near and far field region, which may be the reason that seismicity in these region is higher after the Ms7.3 earthquake.

IASPEI (Seismology, Geophysics)

S04d - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-4198

Areas prone to generation of strong earthquakes in the Andes

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The region under investigation is the Mountain belt of Andes, South America which is well known as one of the most seismically dangerous regions in the world. The problem is to recognize and define the boundaries of the areas, where the strongest earthquake epicenter ($M \geq 7.75$) can be generated. The result has at least two important applications: to focus seismic zoning on these areas and to proceed with the most advanced seismic monitoring within these zones.

To tackle the problem the authors created a new method (FCAZ – Fuzzy Clustering and Zoning) for recognition of highly seismic areas where epicenters of earthquakes with magnitude $M \geq M_0$ can occur. The magnitude threshold M_0 depends on the seismic activity of a region. Following A. Gvishiani, A. Soloviev et al. [1981] $M_0=7.75$ for the Andes. The objects of FCAZ clustering are earthquake epicenters. FCAZ consists of two steps: clustering of known earthquake epicenters by the original DPS (Discrete Perfect Sets) clustering algorithm and obtaining highly seismic zones from the clusters of earthquake epicenters by the original E^2XT algorithm. The FCAZ method was used to recognize areas prone to generation of strong earthquakes in the Andes in this work. Different versions of the maps of the searched highly seismic zones are discussed in the paper according to its reliability.

IASPEI (Seismology, Geophysics)

S04d - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-5456

Recurrence implied by California paleo-seismic data

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Evidence for quasi-periodic recurrence comes largely from California paleo-seismic data, but these data are problematical. A team of experts compiled the most reliable data for use in the third Uniform California Earthquake Rupture Forecast (UCERF3). They reported dates of observed displacements at 32 sites on 13 named faults in California. The problem: recorded paleo-seismic events ceased at about the beginning of the instrumental seismic era, a result inconsistent with the inferred and modeled rates before that time.

The reported event rates for the ensemble of 32 sites sums to about 0.1 per year. Allowing generously for occurrences of earthquakes that rupture multiple sites simultaneously, the event rate is on the order of 0.04 per year. Yet the most recent paleo-event date is 1916. Such a long open interval would be extremely unlikely for a Poisson process and even less probable for an ensemble of quasi-period processes.

Possible explanations for the discrepancy include (1) extreme luck, (2) unexplained regional fault interaction, or (3) mistaken identification of near-surface displacements as evidence of large earthquakes. The first can be rejected with 99% confidence. There is no evidence for the second in the pre-1916 paleo-seismic history nor in any theoretical models yet published. The third could explain the observed quiescence because mistaken identity would be prevented by instrumental seismic data. In any case the inferred rates cannot be taken as long-term averages, and the implied recurrence can’t be trusted for the next century because they fail the last one.

IASPEI (Seismology, Geophysics)

S04e - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-0247

Modelling of hydro-tremors generation and associated hazard in the Northern parts of India

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The hydro-tremors (M_w< 3) have been explained by a mechanism that takes into account the entrapped air/gas in pore spaces of soil above water table which gets compressed maximum due to the actual pore-fluid pressure following heavy rainfall, and upon relaxation of pore-fluid pressure i.e. due to the horizontal diffusion of near surface water, the pressure of the compressed air/gas oscillates, and this causes hydro-tremors to generate as the occurrence of intraplate earthquakes, regardless of the host tectonic regime.. Phenomena of hydro-seismicity caused by the hydrologic triggering of earthquake (M_w> 3) activity on critically stressed faults have been observed in many regions of the world. The associated hydro-tremors generate elastic waves which shake the ground and causing other hazardous phenomena like ground rupturing, subsidence, developments of cracks in the building etc. Sudden relaxation of compressive pore-fluid pressure causes effective stress to develop along the horizontal direction and escape from the capillary channels through the soil to the surface, rupturing the ground surface. The incidences of ground rupturing have been found in areas, experiencing depleted amount of rainfall over the years coupled with withdrawal of subsurface water, and have been reported from many parts of the northern states of India. It has been observed that the increased difference of energy of the compressed air/gas inside the soil produces noisy sound energy during its escape. A speculative model has been presented to study the causative effects.

IASPEI (Seismology, Geophysics)

S04e - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-0546

Synthetic earthquake catalogs simulating seismic activity in the Corinth Gulf, Greece, fault system

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The characteristic earthquake hypothesis is the basis of time-dependent modeling of earthquake recurrence on major faults. However, the characteristic earthquake hypothesis is not strongly supported by observational data. Few fault segments have long historical or paleoseismic records of individually dated ruptures and, when data and parameter uncertainties are allowed for, the form of the recurrence-distribution is difficult to establish. This is the case, for instance, of the Corinth Gulf Fault System (CGFS), for which documents about strong earthquakes exist for at least two thousand years, although they can be considered complete for M > 6.0 only for the latest 300 years, during which only few characteristic earthquakes are reported for individual fault segments.

The use of a physics–based earthquake simulator has allowed the production of catalogs lasting 100,000 years and containing more than 500,000 events of magnitudes > 4.0. The main features of our simulation algorithm are (1) an average slip rate released by earthquakes for every single segment in the investigated fault system, (2) heuristic procedures for rupture growth and stop, leading to a self-organized earthquake magnitude distribution, (3) the interaction between earthquake sources, and (4) the effect of minor earthquakes in redistributing stress.

The application of our simulation algorithm to the CGFS has shown realistic features in time, space and magnitude behavior of the seismicity. These features include long-term periodicity of strong earthquakes, short-term clustering of both strong and smaller events, and a realistic earthquake magnitude distribution departing from the Gutenberg–Richter distribution in the higher magnitude range.

IASPEI (Seismology, Geophysics)

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IUGG-0977

Microseismic study of blocked media response to external impacts

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Spreading of middle-ocean ridges results in seismic events on platforms (Grachev et. al., Yudahin et. al., Skordas et. al.). Mechanisms of ridges impact are associated with shocks like the ones produced by a dyke intrusion. This assumption can be verified by a modeling on natural objects, which resemble crustal blocks processing external impacts.
Artificial dams built of clay and boulders are an excellent example of a natural model. Two types of impacts were studied by the recording of microseisms contained the seismic response of a dam to these impacts. The first one is altering in magnitude and due to the water level change during the tide. It corresponds to a general case, for example being the seismicity of Fennoscand associated with Middle Atlantic Ridge. The second type is shock impacts that resemble lithosphere slabs repulsively pushing from ridges.
The chosen frequency range (0.5 - 70 Hz) in experiment is sufficient for the study the moving of blocks as a whole and the boundary processes. Experimental results discussed show that both types of impacts cause a constraint-bending response. Microseism increase and decrease followed to sea-tide. The high-frequency micropulses can be associated with the seismicity of platforms. The efficacy of the transmission of impact energy into the seismic radiation reaches 1%.
Results serve as another proof of the relation between the platform seismicity and ridge spreading. Practical application is a forecasting of platform seismicity important for seismic hazard estimation.

IASPEI (Seismology, Geophysics)

S04e - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-1019

Time variations in tidal responses of a medium before the Great Japanese Earthquake.

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The method of continuous tectonic stresses monitoring in seismically active regions, based on analyzing the tidal response time behavior, was suggested by C. Beamount and J. Berger [Beamount C., 1974]. It was shown for simplest models of an isotropic medium, that the relative variations in the amplitudes of tidal response (the tilts and strains) have the same order of magnitude as the changes in the scalar shear modulus at a distance of a characteristic size of the source. The Tohoku earthquake at March 11, 2011 in Japan provides a unique possibility to check the idea of Beaumont and Berger, who presumed that the earthquakes could be forecasted by continuous monitoring the time behavior of tidal responses of the media. The goal of this work was to analyze the time dependence of tidal response, observed at nearest to the epicenter F-net seismic stations three years before, and one year after the Tohoku earthquake. New method for determining the time changes in the tidal response of a medium was developed and applied in this study. Slow linear increase of tidal tilts amplitudes before the earthquake and fast decrease of tidal tilts amplitudes after the earthquake were detected. Such kind of tidal response time-dependence is in good agreement with the results of Beaumont ad Berger’s theoretical estimations: the tidal tilts amplitudes increase is connected with accumulation of tectonic stresses before earthquake, whereas their fast decrease is connected with stress relaxation after the earthquake.

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IASPEI (Seismology, Geophysics)

S04e - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

IUGG-1098

Seismogenic structure of the M6.3 Kangding earthquake sequence on 22 Nov. 2014, Southwestern China

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Based on the waveform data from national and regional networks in Sichuan, southwestern China, the 22 Nov. 2014 M6.3 Kangding earthquake sequence along the central NW-striking Xianshuihe fault zone has been relocated by a multi-step locating method developed by Long et al.. The focal mechanism solutions as well as the centriod depths of the 22 Nov. M6.3 and 25 Nov. M5.8 Kangding earthquakes have been inversed simultaneously by the gCAP (generalized Cut and Paste) method. By integrating all of these results, we aim to analyze the seismogenic structure of the Kangding earthquake sequence. The main results are as follows: The best double-couple solutions reveal strike 143°/dip 82°/rake -9° of nodal plane ?for the M6.3 earthquake, and strike 151°/dip 83°/rake -6° of the nodal plane ? for the M5.8 earthquake. This nodal plane was interpreted as the coseismic rupture plane for both earthquakes from the aftershock distribution and the fault strike. The M6.3 earthquake and its first 3 days aftershocks are on the Selaha fault, while the M5.8 earthquake and its adjacent aftershocks are on the northern end of the Zheduotang fault. Relocations of the two events on two different faults indicate that the M5.8 earthquake may be induced by the M6.3 earthquake. The M6.3 and M5.8 Kangding earthquakes are both within the Selaha seismic gap, therefore, we suggest that the ruptures of the two earthquakes are too limited to fill up the gap, thus posing potential further M7 earthquake risk on the Selaha and the adjacent Qianning segment.

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IUGG-2960

Distinguishing artifacts of earthquake catalog errors from genuine seismicity patterns

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Quantitative characterization of spatio-temporal seismicity patterns in relation to physical properties of the lithosphere is a fundamental problem of seismology. Recently, we approached this problem by using new statistical tools for identification and classification of seismicity clusters in the uniform high-quality southern California catalog of Hauksson et al. (2012). This led to recognition of three basic types of clusters: bursts in relatively cold areas, swarms in relatively hot ones, and distributed singles consisting of isolated events without foreshocks, aftershocks. The commonly used Epidemic Type Aftershock Sequence (ETAS) model accounts only for the burst-type clusters. Extending these results to other seismically active areas and lower magnitude ranges, as well as to studying induced seismicity, however, is impeded by inferior quality of available data. Most available catalogs are based on non-uniform recordings that lead to non-uniform location errors, varying magnitude of completeness, and other problems. These non-uniformities produce artificial patterns in the space-time-magnitude clusters of seismicity. In this work we document the effects of catalog errors on inferred cluster properties, and report some striking patterns that emerge as artifacts of those errors. This includes (i) inflated distance-to-parent, (ii) underestimated offspring productivity, (iii) overestimated background rate, (iv) apparent magnitude dependence, (v) fluctuations in the proportion of singles, and other effects. We propose a generalization of our method that involves assigning multiple possible parents to each event, and discuss some graph-theoretic techniques that may provide results that are more robust to location errors and other catalog deficiencies.

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S04p-331

Recovering period of postseismic fluid pressure in fault valve

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The present study aims to reveal the recovering period of the postseismic fluid pressure in fault zone, offering an insight into earthquake recurrence. A two-dimensional layered fault-valve model is proposed for the earthquake fault structure of fluid activity. In order to demonstrate the features of postseismic fluid pressure in natural state, the interference of tectonic movements is not considered. The recovering period of the postseismic fluid pressure includes a sudden-changing period and a much longer fluctuating period. Numerical modeling is performed to simulate the fluid flowing activity based on finite element method. Modeling results show that fault permeability and porosity are sensitive parameters and reversely proportional to the recovering period of the fluid pressure in earthquake fault zone. As the permeability reduces from 10 to the negative15th power square meters to 10 to the negative 18th square metres, the recovering period increases from 400 years to 2000 years, correspondently. The upper and lower fluid pressures are separated by the valve seal, causing their fluctuations in opposite tendencies.

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Extraction of crustal deformation from seafloor hydraulic pressure gauges to estimate interplate coupling for subduction plate boundaries

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To estimate seismic plate coupling and crustal deformation near the trench along the Nankai Trough, we perform a trial simulation of earthquake cycle in the Tonakai district, applying a rate- and state dependent friction law on the plate boundary and assuming the 1944 Tonankai earthquake and slow earthquakes occurring in numerous small asperities.

Our simulation suggests that the observed activity of the shallow slow earthquakes locally around the fault segmentation boundary between the source regions of the Tonankai and Nankai megathrust earthquakes may be due to weak coupling between the two segments, while quiescence of the shallow slow earthquake around the segmentation boundary between the Tonankai and Tokai megathrust earthquakes may indicate strong plate coupling between the two segments.

To evaluate these characteristics quantitatively, we also estimate leveling change at seafloor due to shallow VLFE swarms. Since the levelling change is expected to be so local as to be incoherent, removal of the moving-averaged data from the data stacked by four nearby observation point in the same node may be useful to detect the short-term local levelling change.

In the future, we have to extract the crustal deformation component by separating other components such as instrumental drift and oceanic changes in order to consider coherent change among the same science node.

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Long period anomalous tremor wave and its characteristics before a violent earthquake

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In the continuous waveform data of the seismological observation, we often found out that there are some abnormal microseisms. Some of the microseisms are aroused by the tropical cyclone in the Western Pacific, and others are mostly accompanied by violent earthquakes, called anomalous tremor wave. Before a violent earthquake, there is an indisputable fact that a long period anomalous tremor wave, which duration for several hours and period up to ten seconds, can found and observed in the continuous waveform data of the continent seismological observation of China. This paper mainly studies that the space-time distribution and frequency spectrum characteristics of the long period anomalous tremor wave which observed by the continent seismological station of China before Ms7.0 earthquake, analyzes and discusses these signals associated with the possibility of violent earthquake. The preliminary researches show that the corresponding rate observed this long period wave can be up to 80% in ten days before Ms7.0 earthquake occurred, and have a certain repeated activities characteristics of the cycle. Among them, the excitation source of many signals with cycles over tens of seconds is within 200 km range of the observation stations, can represent and reflect the movement of the tectonic fault near stations and stress state. Therefore, research and analysis of the anomalous tremor wave may provide an effective way for further understanding a generation process of earthquake, the earth dynamics and earthquake precursors.

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Earthquake source scaling and non-self-similarity of Kachchh, Gujarat.

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This paper discusses the interrelationships of scaled energy, apparent stress, seismic moment, stress drop and corner frequency, which are measured through the Levenberg-Marquardt non-linear inversion modeling of S-wave displacement spectra for 489 selected earthquakes (Mw 2.05-5.52) from the 2001 Mw7.7 Bhuj earthquake sequence. We notice that our estimated corner frequency and seismic moment satisfies the relation Mo ∝ fc-(3+ε), where ε (measure for deviation from self similarity) is found to be 1.33 for the larger earthquakes (Mo > 2x10^15 N-m) while the parameter ε is estimated to be 6.74 for smaller earthquakes (Mo < 2x10^15 N-m). We also notice that stress drop increases with seismic moment, approximately as Mo^3 (E ∝Mo^3) for smaller events (Mo<10^15.3 N-m) while for larger earthquakes (Mo < 2x10^15 N-m) stress drop increases approximately with Mo1 (E ∝ Mo^1). Adding credence to this non self-similar theory, our estimated seismic moments and source radii (r) also reveal a break in linear self-similar source scaling at Mo=2x10^15 N-m and r=300 m, which is attributed to constant source radius for smaller earthquakes. We also compare between estimated apparent stresses and static stress drops, which suggests a frictional overshoot mechanism for larger earthquakes while smaller shocks are showing both partial stress drop and frictional overshoot mechanisms. Thus, we hypothesize that larger events are subject to the regional state-of-stress, whereas smaller earthquakes are sensitive to the local state-of-stress associated with material heterogeneities and fluid flows within the fault zone. The interrelationships between various source parameters developed in this study could be useful for accessing proper seismic hazard in the region.

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Seismicity and geometry properties of the Hellenic subduction zone

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Recent seismicity and earthquake focal mechanisms along the Hellenic Arc–Trench system are engaged for approximating the geometry of the subducted oceanic plate. The gentle subduction (~15°–20°) of the oceanic crust reaching a depth of 20 km at a distance of 100 km from the trench is confirmed. The slab is then bending at larger angles, and in particular at ~45° up to the depth of 80 km and at ~65° up to the depth of 180 km, when seismicity ceased. This slab geometry is shown in a bunch of cross sections normal to the convergence strike, up to ~25°E (east Crete Island). To the east the sparse inslab seismicity reveals an almost vertical dipping of the lower part (from 80 km downdip) of the descending slab. The slab interface that accommodates hazardous earthquakes is clearly nonplanar with the main seismic moment release taking place on its up–dip side. The fore–arc, upper plate seismicity, is remarkably low in comparison with both subduction and back arc seismicity, and confined inside a seismogenic layer having a width not exceeding the 20km. Offshore seismicity is spatially variable forming distinctive streaks revealing that parts of the oceanic crust are probably slipped aseismically. This observation along with the fact that coupling in the Hellenic arc is only about a tenth of the plate motion, imply the presence of areas of lower and higher coupling across the subduction interface.

This research has been co–funded by the European Union (European Social Fund) and Greek national resources under the framework of the “THALES Program: SEISMO FEAR HELLARC” project.

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Seismicity properties in the Western part of Corinth Gulf (Greece) revealed from relocated earthquake catalog

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The western part of Corinth rift is one of the most seismically active areas in the Aegean and its surroundings. Several destructive earthquakes have damaged the area both in historical and instrumental era but mainly the seismicity is manifested with the occurrence of numerous small magnitude shocks. The physical process responsible for this kind of microseismicity is examined in the present study. For that purpose an earthquake catalog with highly accurate locations is necessary in order to define the involved structures and investigate temporal properties of the microseismicity. The double difference technique was employed along with differential times derived from cross correlation measurements in order to compile the seismicity catalog of the area. The recordings of approximately 55 stations of the Hellenic Unified Seismological Network (HUSN) operating during 2008-2014 and located in epicentral distances less than 160 km from the target area were used. P and S phases were gathered from the monthly bulletins of the Geophysical Laboratory of Aristotle University of Thessaloniki and the National Observatory of Athens (NOA) along with manually picked ones. Faults and small segments are clearly depicted from the relocated catalog along with spatiotemporal characteristics of the seismicity. The revealed structures and their interactions contribute to the understanding of earthquake generation in the area and give new insights of the current fault system.

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On the foreshocks of strong earthquakes

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We used the general ideas and concrete results of catastrophe theory and the theory of critical phenomena for analysis of the foreshock dynamics within a few hours before the main shock. Main attention was paid to the sharp rise in fluctuation level, the increase of reactivity of dynamical systems in the near-threshold region, and to other anomalous phenomena which are similar on the critical opalescence. In the absence of a sufficiently complete theory of earthquakes such an approach to the analysis of the observations it becomes quite reasonable. As a result, we succeeded in finding some non-trivial properties of the source of strong earthquake that manifest before the formation of the main discontinuity of rocks at the mainshock. In the course of our study the ideas of round-the world seismic echo and cumulative effect of converging surface waves have been created. Activation of the foreshocks three hours before the main shock has been discovered. It is hypothesized that the round-the-world seismic echo signals from the earthquakes, which form the peak of energy release 3 h before the main events, act as the triggers of the main shocks due to the cumulative action of the surface waves converging to the epicenter. It is established that the frequency of the fluctuations in the foreshock activity decreases at the final stages of the preparation of the main shocks, which probably testifies to the so-called mode softening at the approach of the failure point according to the catastrophe theory. Further research in this direction seems interesting and promising. The work is partly supported by Russian Foundation for Basic Research (grant 15-05-00491), and Presidium of the Russian Academy of Sciences (Program 4).

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Strong ground motion simulation of 2012 earthquake doublet in Azerbaijan region, Iran

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On August 11, 2012, within 11 minutes, two shallow destructive earthquakes with magnitudes of 6.5 and 6.4 occurred in Varzagan, in Azerbaijan region, northwestern Iran, approximately 300 km east of the plate boundary between the Eurasia and Arabia plates. Two earthquakes were separated by just 10 km in an east-west direction. The earthquake doublet we discuss here, have similar magnitudes (Less than 0.2) and occurred within a short distance of each other; also, there is short delay between the two events. The focal depth of the first earthquake was calculated as 9 km, the second event occurred in the same region but its depth was 2km less than the first one. In this study, to estimate source parameters and rupture characteristics of the earthquakes, strong ground motion simulation method was used. To simulate the first earthquake, two aftershocks with magnitudes of 5.6 and 5.2 were used as the empirical Green functions. In the second event, an aftershock with magnitude of 5 was used as the small event. The size of the main fault caused by the first event was about 18km in length and 10 km in width. Also the size of the asperity in the second earthquake was about 16km in strike direction and 11 km in dip direction. The durations of the ruptures in the first and second events were about more than 9 and 10s, respectively. The estimated fault plane solution shows strike-slip faulting for the first earthquake and reverse mechanism with strike-slip component for the second one. Strike, dip and rake of causative faults of the first and second earthquakes were determined as 270, 81 and -175 degrees and 230, 57 and 134 degrees, respectively. In addition, the stress drop in the first and second events was calculated to be about 22 and 34 bar, respectively.

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The impact of the geomagnetic storm sudden commencement on the global seismicity

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We have investigated statistically the problem of possible impact of the geomagnetic storm sudden commencement (SSC) on the global seismic activity. SSC are used as reference points for comparative analysis of seismicity by the method of superposed epoch. We selected 405 earthquakes from 1973 to 2010 with magnitudes ?>=5 from a representative part of USGS catalog. The comparative analysis of seismicity was carried out at the intervals of ±60 min relative to the reference point. With a high degree of reliability, it was found that before the reference point the number of earthquakes is noticeably greater than after it. In other words, the global seismicity is suppressed by SSC. We refer to some studies in which the chemical, thermal and force mechanisms of the electromagnetic field action on rocks are discussed. We emphasize the incompleteness of the study concerning the correlation between SSC and earthquakes because we still do not succeed in understanding and interpreting the relationship in terms of physics and mathematics. The study need to be continued to solve this interesting and important problem. The work is partly supported by Russian Foundation for Basic Research (grants 15-05-00491 and 13-05-00066), and Presidium of the Russian Academy of Sciences (Program 4).

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S04p-340

Astronomy chronograph of strong earthquakes and volcanism

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The role of tidal effects on geospheric shells from the Moon, the Sun, Venus, Mars and Jupiter is examined. The impact of specific configurations of the Sun and the planets (in the line of apsides, equinoxes, solstices) on the catastrophic geophysical processes such as anomalous seismicity and volcanism.

The histogram distributions of earthquakes and volcanic eruptions, depending on the distance Earth-Sun, the ecliptic latitude of the Moon, the geocentric longitude differences of Sun and Venus or Mars are adduced. This astrogeophysical approach allowed to identify global relationships of planetary nature.

Particular attention is paid to the analysis of well-known and paradoxical cases of and mutual influence of seismic and volcanic activity:

- A powerful earthquake in Chile (1835.), followed by the awakening of several volcanoes;

- Tunguska phenomenon(1908) as a volcanic earthquake with advanced gas phase and high-altitude undermine the degassing of hydrogen-methane stream from the crater of Kulikovskii paleovolcano;

- Dramatic activation in mid-1908 of Mount Etna in Italy and Erebus in Antarctica and subsequent Messina earthquake with the formation of a powerful tsunami and ejection of giant steam-gas jet height of 8 km on the pass between Erebus and Mount Baird;

- Unexpected and powerful awakenings of Kamchatka after a swarm of earthquakes volcanoes Bezymyannyi (1956) and caldera of the Academy of Sciences (1996).

The work was carried out with the financial support of the Ministry of education and science of the Russian Federation (in accordance with the requirements of the State contract ?14.577.21.0109).

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Synthetic catalogue simulated by quasi-static/dynamic model and its implication on the estimation of the regional seismic hazard at Friuli, Italy

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A quasi-static/dynamic model developed by Zhou et al.(2006) is used to simulate the seismicity at Friuli region of Italy. A synthetic catalogue with 10,000 years duration is generated . Comparing the simulated seismicity to the observed seismicity, we find that the seismic rates of the simulated seismicity are quite consistent with the observed seismicity for the earthquakes with $Ms<6.0$, and their b values are 0.94 and 0.95, respectively. The seismic rate of the simulated seismicity for the earthquakes with $Ms\geq 6.0$ is 0.02/year, which is much smaller than the observed one (0.17/year). The fault interaction matrices and the strong shock transfer possibility matrices among the main faults of Friuli are inferred based on large samples of strong shocks of the simulated catalogue, which provides important messages for estimating the regional seismic hazard at Friuli. The simulated catalogue with long duration could also provide a useful database to calculate the seismic risk using statistical methods and to develop or test earthquake precursors and earthquake prediction models.

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Analytical understanding of slip velocity in the steady state of dynamic earthquake slip in the system with fluid flow

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We have constructed the framework associated with the interaction among heat, fluid pressure and inelastic pore creation to explain many aspects of dynamic earthquake slip process. In particular, two qualitatively different behaviors, acceleration with final high-speed slip and spontaneous slip cessation, are found in the framework. However, our previous treatments assumed no fluid flow case. We employ the fluid flow effect analytically in the present study and the steady state value of the slip velocity is investigated.

To obtain the slip velocity in the steady state, we first treat temporal evolution of the normalized frictional stress P*. The term dP*/dt* consists of summation of the source term due to fluid pressure change induced by slip and the diffusion term. First, we consider the area outside of the slip zone. Because the source term vanishes there, the diffusion term is zero in the steady state. With this statement and boundary condition (the absolute value of P* should be finite at |y*| \to infinity), we can conclude that P* is spatially constant. In addition, if the constant value is not zero, infinite pore creation and infinite fluid pressure reduction is required to balance the fluid pressure rise due to the shear heating. Since this is obviously impossible, we have P*=0 over the whole space outside of the slip zone. Additionally, if the average value of P* inside of the slip zone (<P*>) is not equal to zero, the fluid flow into the zone raises the fluid pressure there, which contradicts the assumption that <P*> is not zero. Therefore, we can conclude that <P*>=0 must be satisfied at the steady state when the fluid flow is allowed. This leads to the high-speed slip, which is the same behavior as that of the acceleration case without the fluid flow.

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Simulation study of the influence of medium viscosity on aftershock activities

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Assuming the rupture of the residual asperities inside the mainshock fracture plane randomly leads to the aftershock, the size of the residual asperities conforms to fractal distribution, and the rupture or instability strength of the residual asperities accords with the lognormal distribution. Taking the postseismic stress relaxation as the mechanical load , the loading stress is attenuated in negative exponential rule. Taking the Coulomb failure criterion as the judgment rule of the instability, combining the mechanical interactions among the residual asperities, the artificial aftershock sequence, including occurring time, location and magnitude, are simulated under different conditions. The agreement between output and the actual statistical characteristics of aftershock activities is detected by G-R relationship and modified Omori formula as a basis for further adjustments to the model parameters. On this basis, the influences of the medium viscosity properties on aftershock activities have been discussed. The results show that viscosity coefficient operates an important rule on the duration and decay rate of the aftershock activity, p value, the decay rate of modified Omori law, changes with the viscosity coefficients according the negative exponential function. The G-R relationship of the aftershock sequence is irrelevant with the viscosity coefficient, it is mainly controlled by the size distribution of the residual asperities. In another words, it is mostly correlative to the heterogeneity of tectonics and medium.

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Estimation of source parameters in the Makran Region using body wave Spectra of the six recent great earthquakes

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The Makran subduction zone is located offshore Iran and Pakistan from the Strait of Hormoz, in the south of Iran to near Karachi in Pakistan. The seismicity of Makran is low compared to other subduction zones and the eastern and western parts of Makran exhibit different patterns of seismicity. In this study we determined source parameters of Makran region include seismic moment, corner frequency and stress drop using displacement spectra of P and S waves observed at stations of Iranian National Broad-Band Seismic Network (INSN). In this regard, three-component records of six great earthquakes located in Makran region with the magnitudes M6.2–M7.8 between 2005 and 2015 were used. The spectra of the records were corrected for attenuation, then source parameters retrieved by fitting a Brune’s point source model. The stress drops of individual earthquakes range from about 6.6 to 45.5 bars. The average stress drop obtained in this research for the Makran is about 43 bars that is in good agreement with other studies in the same tectonic regimes of the world.

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M9 Tohoku earthquake response in Caucasus – possible local tremors and hydroseismic effects

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Presently, there are a lot of observations on the significant impact of strong remote earthquakes on underground water and local seismicity regime (so called nonvolcanic or dynamical tremors). On the other side, teleseismic wave trains of strong earthquakes give rise to several hydraulic effects in boreholes, namely water level oscillations, which mimic closely seismograms (hydroseismograms). Both these effects are closely related to each other as one of main factors reducing the local strength of rocks is the pore pressure of fluids.

Some evidence of possible dynamic triggering from great Tohoku (M9) earthquake has been obtained recently in the Caucasus. Besides tremors, clear identical anomalies on the large part of territory of Georgia from Borjomi to Kobuleti in the deep borehole water levels has been observed at passing S- and Love-Rayleigh teleseismic waves of Tohoku earthquake. We presume that coincidence of possible tremor signal with water level anomaly (oscillation) makes much more reliable event classification as a triggered one. We also report a new observation on water level oscillations during passage of multiple surface Rayleigh waves.

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S04p - S04 Earthquake Generation Process: Physics, Modeling and Monitoring for Forecast

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On the free oscillations and auto-oscillations of the Earth

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The notion of free (proper, eigen) oscillations is one of the most important in seismology. We have observed recently the impact of Earth’s free oscillations with period 54 min on the activity of earthquakes. On the other hand, it is well known that the free oscillations are excited by the earthquakes. In this context, the question arises naturally: Should we not to consider hypothesis of the existence of auto-oscillations of the Earth? Basis of general considerations the hypothesis is not objectionable because the Earth is an autonomous, non-conservative and non-linear dynamical system. We have analyzed the issue and have come to the following conclusion. The impact of Earth's free oscillations on the global seismicity is interesting in itself. However, this effect is not testifies to the existence of Earth's **self-oscillations of the resonant type**. At the same time it is not excluded that the signs of **relaxational self-oscillations** are sometimes observed after strong earthquakes in the form of hidden recurrence of the aftershocks with quasi-period of about three hours. The work is partly supported by Russian Foundation for Basic Research (grant 15-05-00491), and Presidium of the Russian Academy of Sciences (Program 18).

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Grain size segregation without gouge fluidization

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The structures and textures of fault gouge are believed to provide with rich information on the coseismic slip dynamics of faults. In Chelungpu fault gouge, where the coseismic slip was accommodated in 1999 Chichi earthquake, grain-size segregation is found [Boulier et al. G^3 10, Q03016 (2009)]. This could be an evidence for gouge-fluidisation, because grain-size segregation is believed to require sufficient porosity in granular matter. Ujiie and Tsutsumi [GRL 37, L24310 (2010)] also find grain-size segregation in a laboratory friction experiment with large displacement (~12m) and under intermediate normal stress (~2MPa). Here we wish to know whether grain-size segregation occurs as a result of gouge fluidisation, and in a short duration that may be relevant to coseismic slip. To this end, we perform numerical simulation on a simple model of fault gouge, and show that grain size segregation occurs under a condition that may be relevant to faults gouge: the pressure of 1 MPa, the sliding velocity of 1 m/s, and the duration of 0.1 sec. Segregation occurs irrespective of gravitation and it is controlled by nonlinear velocity gradient. More importantly, we find that segregation occurs even if the granular matter possess yield stress, and therefore segregation itself does not imply gouge-fluidisation.

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A Seismic Gap on the Middle Segment of the Red River Fault Zone, Yunnan, China, and its Earthquake Potential

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On the middle segment of the Red River fault zone (RRFZ) of Yunnan, China, there have been no major earthquakes for long time. Our study shows that, this fault segment is active in the Holocene, and more evidence about the Holocene faulting and paleo-earthquakes have been found recently. From a historical seismicity study, a seismic gap without major earthquakes is identified on this fault segment. On modern seismicity, this gap displays as a fault section without or with very few small earthquakes, but is surrounded by areas with low b-values, indicating relatively high stress existing there. Also, GPS deformation and stress field analyses suggest that this fault segment is a tightly locked one. These reflect that the middle segment of RRFZ has long-term seismic potential of major earthquake. Also, it has been inferred that, the long-lasting locking on this fault segment has made the high stress area, which centers at the locked fault segment, spreads gradually toward two sides of the segment, and has increased stress there. Such spreading may have possibly increased seismic potential on some secondary faults of the two sides of the fault segment, especially on the parallel Chuxiong fault. In additional, a moment magnitude of the potential earthquake on the middle segment of RRFZ is estimated to be MW =7.8 to 8.1.

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A static-dynamic cellular automaton model on a Tokunaga network for the description of distributed seismicity

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We propose a modification of the cellular automaton model of distributed seismicity introduced by Tejedor et al. (Phys Rev E **82**, 016118, 2010). In that paper we devised a hierarchical model to simulate the seismicity in a region. The model was able to account for several important regularities of real seismicity, but it also had two basic shortcomings: (i) a too rigid fault hierarchy where a fault of (discrete) size N is in direct contact only with faults of sizes N-1 and N+1; and (ii) an intrinsic inability to sort aftershock in temporal order.

The modifications that we are proposing here deal with both shortcomings. To relax the rigidity of the hierarchy of the previous tree structure, we construct the new model on a Tokunaga self-similar network with parameters (a, c); in this way a fault of size N can be in direct contact with faults of any size. To circumvent the problem of the simultaneity of all the aftershocks of a mainshock, we switch to a time-dependent formulation: once an external stress particle has triggered an earthquake in the model we can follow in 'real time' the progress of the cascade as stress particles are transferred from failing faults to neighboring faults. The switch from a static to a time-dependent failure mode in the model is compatible with the two basic mechanisms by which earthquakes occur: mainshocks are the result of stress accumulation followed by failure; aftershocks are the result of time-dependent creep failure.

This model aims to reproduce the following key observables of real seismicity: a size-frequency relation of the Gutenberg-Richter type with the correct b value (both for all earthquakes and for mainshocks only), and a decreasing rate of aftershock production à la Omori’s law.

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The focal mechanism of crustal events from Vrancea region (Romania) estimated by local waveform inversion

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The crustal seismicity of Vrancea region (Romania) occurs over a rather broad region in the Southeastern Carpathian foreland; it is moderate-sized (not exceeding magnitude 5.6), and, by comparison to the mantle seismicity, it was less investigated by now. Nevertheless, the crustal deformation in front of the Carpathian bend, as well as its relationship to the Vrancea intermediate-depth seismogenic zone motivate significant scientific interest.

The low rate of occurrence of moderate-size earthquakes and the poor seismic instrumentation before the last decades of the XXth century, resulted in a rather modest collection of reliable seismic source mechanisms in the area.

A local waveform inversion scheme requiring only few good quality records has previously been tested on a pilot set of crustal Vrancea earthquakes with local magnitudes less than 4. For 7 out of 9 investigated events, the procedure led to acceptably constrained fault plane solutions.

Following the same approach, improved structural models are considered for the computation of the Green's functions in the present study: revised crustal velocity models, compiled from data available in recent literature, and local models for the quality factor of the medium Q, estimated using the high frequency waveform modelling.

The use of optimized structural models has resulted in a significant increase of the reliability of the retrieved fault plane solutions, pointing out the capability of the local waveform inversion method to estimate confidently the focal mechanism of the normal depth earthquakes with local magnitude around 4. This opens perspectives for a detailed exploration of the crustal deformation field in Vrancea region.

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Clear evidence of precursory patterns in aggregated seismicity time series

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A major target in seismology is to try to develop methods for reliable short-term warning of coming large earthquakes. Many phenomena prior to large events have been investigated in order to assess their possible predictive power, generally with limited success. The most obvious family of such phenomena are those related to temporal changes in seismicity patterns prior to large events. We investigate inter-event times between temporally neighboring or near-neighboring events in a defined area as a time-specific proxy for seismicity rate. Possible earthquake-generating processes prior to larger events and processes after such events relate to the response of a similar volume of the Earth to stress changes, and therefore we investigate possible foreshocks, seismic quiescence and aftershock sequences. Using catalogue data from Greece we were unable to unambiguously identify precursory changes in seismicity before individual larger events, i.e. where changes in activity could be seen the patterns were insufficiently clear and consistent in order to judge these to be precursory activity, as opposed to some more unrelated phenomenon. However, when our proxy seismicity-rate data before many events was aggregated, a clear pattern emerged, with an acceleration in seismic activity for about a month prior to the events. This feature was found even in separate subsets of the data. This implies that genuine precursory signals do exist, but that the existing data was insufficient to identify the signals in individual cases; thus, significantly more sensitive networks might be very helpful when seeking precursory activity. We are now using similar tools to investigate data from Iceland where the advanced and highly sensitive network detects and analyses very small magnitude events.

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Timing of peak rates and largest magnitude events in volcanic earthquake swarms

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We present results of recent diagnostic studies of volcanic earthquake swarms, a type of induced seismicity. A clear pattern is that peak rates often occur early in swarms, whereas the largest M event occurs late. Using data of 20 swarms from the literature, swarm durations were 12 h to 6 mos., measured from swarm onset to eruption onset. Data were normalized to % duration. Peak rates occurred from 1-42 % of the way through swarms, and largest M event occurred 32-99 % of the way through. Additional evidence from 4 cases suggests that the seismic source size grows systematically. This is revealed in plots of M versus time for event families. For comparison, 19 cases of mid-ocean ridge (MOR) swarms were analyzed. These show durations of 1-42 days, with peak rates occurring 1-24 % of the way through and largest M occurring 1-87 % of the way through. In 6 cases the largest M occurs before or at the same time as peak rate. Thus the pattern for MOR swarms differs significantly from that for volcanic swarms. Further work on volcanic swarms shows that the distribution of seismicity before the peak rate differs from after, suggesting two dominant processes. The durations of post-peak portions are roughly proportional to the peak rates, similar to aftershock sequences. The portions of the swarms prior to the peaks behave differently, however. These may represent the invasion of hot fluids and the opening of cracks prior to magma intrusion. We infer that the growth in event size reflects activation of a preferred magma pathway. Recognition of such patterns, linked to processes, may improve monitoring and reduce risks from eruptions. Comparison is recommended between the patterns observed here and those associated with induced seismicity from fracking and deep well injection.

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On relationship between variations in solar activity and seismicity

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For development of reliable methods for earthquake prediction, it is desirable to have complete knowledge about the physical causes that generate earthquakes. As such knowledge is not yet available, it seems appropriate to continue research to identify patterns in variations of seismicity in connection with variations of other physical events. This report deals with connection of seismicity with solar/cosmic rays variability. On base of global seismological catalog NEIC (182933 events with $M \geq 4.5$ for 1973-2011) we show:

- the long-term trends in yearly mean earthquake counting rate and released seismic energy as well are out of phase with long-term trend in yearly mean sunspot numbers;

- into the 11 year solar cycle, earthquake counting rate is relatively small for years with moderate solar activity, but is increased at ~10-12% in solar minimum, when galactic cosmic rays are increased, and at ~5-7% in solar maximum, when injection of solar charged particles is increased;

- in seismic regions penetrated by geomagnetic force lines L=2.0-2.2 which are populated by anomaly cosmic rays with pronounced dependence of their intensity on solar activity, strong earthquakes ($M \geq 7.0$) occur only at declining phase of 11 year solar cycle, but absent at ascending phase, this already may be used as a long-term earthquake precursor for these regions.

To explain the results, it is suggested that earthquakes are triggered by currents in the Global Electric Circuit, which show positive response to cosmic ray changes. As a result, agreement between variations of seismicity and solar activity/cosmic rays is evident.

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Numerical simulation of the dynamic rupture process of the 2011 Mw 9.0 Tohoku-Oki earthquake

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Earthquake could be considered as an unstable dynamic process of stress release induced by fault material softening or damage. Based on this idea, a finite element method is proposed to simulate the dynamic rupture process of the 2011 M_w 9.0 Tohoku-Oki earthquake. The displacements, dislocations and stresses predicted by the model with and without asperities are discussed. Main results reveal that: the existence of an asperity does not change the initial tectonic stresses of the fault zone obviously. When an asperity exists, maximum quasi-static shear displacement and shear dislocation on the fault surface of hanging wall are 51 m and 58 m, respectively. Both of them appear at the trench. The difference of the maximum shear dislocations between the models with and without the asperities is not obvious (maximum shear dislocation is 55 m for the model without the asperity). The maximum shear displacement of the foot wall fault surface (-10m) is at the asperity. The maximum shear stress drop at the asperity (about 11 MPa) is larger than that in the surrounding fault area. Maximum normal stress drop (about 3 MPa) appears at the asperity. The predicted results are not favored that the rupture of an asperity is responsible for the unexpected large dislocation of the Tohoku-Oki earthquake instead of the huge damage of fault zone material.

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Earthquake cycles on the bumpy plate interface assuming subducting ridge chain

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Recently, quasi-dynamic earthquake cycle simulations (ECSs) in BIEM (boundary integral element method) have reproduced the earthquake cycles with various slip behaviors on the plate interface including large earthquakes, slow slip, and tremors. These studies always consider only the shear stress change but not the normal stress change due to the slip. However, the normal stress changes due to the slip on the fault interface when the fault interface is not flat but has topography. Therefore, in this study, we introduced the static normal stress change to the quasi-dynamic ECSs in BIEM, and examined the slip behaviors on the bumpy plate interface.

The ridge chain subducts under the Tokai region, central Japan (Kodaira et al., 2004; Hirose and Maeda, 2013), where the next Tokai earthquake is anticipated to occur in the first half of this century. In the deeper part of the Tokai region, there have been observed also long-term slow slip events (SSEs) just beneath the Lake Hamana. In this study, we set the bumpy plate interface assuming subducting ridge chain, and examined the slip cycles on the plate interface. Then, even with the frictional condition that produces repeated normal earthquakes, the bumpy fault interface produced repeated slow slips and the earthquakes. A series of the tops and valleys of the ridges exhibit the increase and decrease in the normal stress during the interseismic period. This striped normal stress change can be the cause for recurring slow slip events around the valley of the ridge chain. This can be one of the mechanism of generating the Tokai SSEs, in addition to the existence of high pore pressure.

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Active foreshock sequences of M>7.5 earthquakes in the northern Japan to Kuril Trenches

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Along the northern Japan to Kuril Trenches, active foreshock sequences preceded some M>7.5 earthquakes, providing a good opportunity to understand the characteristics of foreshocks for large interplate events. Active foreshocks are identified in the M-T diagrams before and after the mainshocks. The earthquakes preceded by active foreshocks are: the 2006 (M 8.3) and 2007 (M 8.1) offshore Simushir earthquakes, the 1963 (M 8.6), 1991 (M 7.6), 1995 (M 7.9) offshore Urup events, the 1978 (M 7.8) offshore Iturup event, the 1969 (M 8.2) offshore Shikotan event, the 1989 (M 7.4) offshore northern Sanriku event. In contrast, M>7.5 interplate earthquakes offshore Hokkaido to northern Sanriku in 1952 (M 8.1), 1968 (M 8.3), 1973 (M 7.8), 1994 (M 7.8), 2003 (M 8.1), and intraslab earthquakes in 1958 (M 8.4), 1978 (M 7.8), 1993 (M 7.7), 1994 (M 8.3) had few or no foreshocks.

Some results from our examination of the foreshock sequences are as follows. Fitting the ETAS model (Ogata, 1988) to foreshock sequences show that the active foreshocks were composed of large foreshocks and their aftershocks. Foreshocks of the 2007 Kuril outer-rise earthquake were interpreted as aftershocks of the 2006 interplate earthquake. Relocated foreshocks show that they migrate in various, not unique, directions. Distributions of foreshock do not overlap with the large coseismic slips (asperities) of the mainshocks of interplate earthquakes. Relocation of foreshocks and maishocks were made by the modified JHD method and time-difference grid-search method (Hurukawa & Harada, 2014). The coseismic slip distributions were estimated by the teleseismic body-wave inversion (Kikuchi & Kanamori, 2003).

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Abnormal GPS baseline length changing before 2013 Ms7.0 Lushan earthquake in China

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On 20th April, 2013, an Ms7.0 earthquake occurred at Lushan county, Sichuan province, China. Five years (2010-2015) observations of six continuous GPS stations near to the epicenter are processed with GAMIT software and two time series of the absolute baseline length change and the angle change between baselines are obtained. Both time series show an abnormal slowdown in three months before the earthquake, then, go back to the normal changing rates after ten months of the earthquake. The physical processes of the earthquake deformation is then discussed under viscoelastic medium assumptions.

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Time-dependent seismicity method based on subsurface fracture parameters for seismic hazard quantitative evolution of blind fault in eastern China

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A large number of facts show that the blind active faults in eastern China has the capability of earthquakes of above magnitude 7. For instant, the Tangshan M7.8 earthquake in 1976 killed over 240000 people. For another example, in 1119 in Songyuan City of Jilin Province happened the largest ever historical earthquake in northeast China, with a magnitude of 63/4. In order to clarify the seismogenic fault of the earthquake, also to study the seismic risk of Songyuan, we had finished a three-year active faults detection project. During the project, we found a blind active fault late pleistocene in the magistoseismic area of earthquake, named Gudian fault. In the project, detailed underground structure of the fault was obtained through three dimensional seismic petroleum data from the intra-area Jilin Oilfield. The latest activities and sliding rate were obtained from the shallow seismic exploration and the terrace borehole work. On the basis of comprehensive study on the geological structure, the quaternary activity, historical earthquakes and modern earthquake activities of the fault, etc, we evaluated the potential maximum earthquake magnitude on subsurface fracture parameters. We confirm the fault to be active since late Pleistocene, with the ability of above magnitude 7 earthquakes. Through some other works, ultimately we put Gudian fault as the seismogenic structure of the 1119 earthquake. In addition, recurrence period or annual rate are calculated by seismic moment ways. Then time-dependent probability model is adopted to calculate the occurrence probability of the Gudian Fault in the coming 50~200 years.

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Observation and simulation of long-period ground motions in the Nankai Trough, southwest Japan

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A dense-array seafloor seismic observatory was deployed in the source area of great subduction earthquakes in southwest Japan in 2010. We present the development of long-period ground motions in the subduction area from the seafloor observation data at a large event (Mw 5.8) occurred in April 2013. The observed seismic waveforms are significantly prolonged and amplified, which does not agree with an empirical relation of amplifications for epicentral distances. We reproduce these features of waveforms at the seafloor stations in the period range of 10-20 s with FDM simulations and demonstrate the effects of seawater and sediment structures in ocean area on seismic wavefields. The long-period motions are predominantly caused by the propagation of surface waves developed within sediment layers in the subduction area. For the motions of the vertical component, the presence of a seawater layer also contributes to the developments. The snapshots obtained from simulation results show more trapped seismic energies and slower seismic-wave propagations in the subduction area than those in the land area, which produces the amplified and prolonged long-period motions at the seafloor stations. The long-period range we analyzed is very important for magnitude estimations and moment tensor and finite-source analyses at great subduction earthquakes. Our observation and simulation results highlight the importance of ocean-specific structures for the seismic wave propagation and would contribute to advancing the seismic source studies by using seafloor station data.

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"The geomagnetic field and the total electron content anomalies and electromagnetic effects connected with the strong earthquakes"

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A complete analysis of studying correlation of seismic activity with nature electromagnetic fields requires select and estimate the contribution of planetary geomagnetic processes and local responses and calculate the ratio of the external (ionospheric) field T_e and telluric variations (lithospheric) δT_i. Necessary to take into account the ionosphere conditions such as the total electron content, wind's velocity, the conductivity and current's density. In this talk proposes a new method of searching and selection electroseismic signals prior to earthquakes (precursory). The method based on the complex analysis of geomagnetic field, nature electric field, seismic field and the total electron content taken together. To highlight electroseismic signals used both classical and modern mathematical methods of analysis such as STA/LTA algorithm, Fourier and consistent filtering, the polarization method.
The complex analysis of the total variations of the geomagnetic field and the total electron content allows calculating the parameters of ionospheric disturbances, and can be used to more effectively searching ionospheric oscillations associated with the strong earthquakes. The results of a complex analysis of the variations of the total electron content and variations the geomagnetic field during the strong earthquakes and the strong geomagnetic storms will be shown. Furthermore, a seismoelectrical effect and a geomagnetic response to ionospheric disturbances caused by Rayleigh waves in the ionosphere are presented.

Acknowledgements
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Teleseismic source parameters of the Iquique Chile, april 2014 sequence of earthquakes

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During March-April 2014 a series of earthquakes occurred around the Iquique city located in the northern Chile region. The northern Chile region has been known to experience several seismic gaps. The April 2014 sequence of earthquakes has been occurred across the central seismic gap close to Iquique city where the down-going slab dips at about 30 degrees. We computed and demonstrated nodal planes of the eight of the large and well teleseismically recorded events of this series based on the grid search and derived moment tensors of the same events based on the deviatoric moment tensor inversion. We corrected the observed seismograms for instrumental response, converted to velocity between 0.004-5 Hz, low-pass filtered at 0.25 Hz and interpolated to the rate of 1 Hz. According to the results both the grid search nodal planes and moment tensors suggest the dominance of reverse faulting. Meanwhile nearly all of the calculated teleseismic moment tensors represent a considerable amount of DC (usually more than 90%) and lower amount of CLVD for this sequence of events.

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Seismic events recorded on the Xishancun Landslide, Sichuan China

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Xishancun Landslide is located about 20 km northwest of the Wenchuan County, where the great 2008 Ms8.0 Wenchuan earthquake occurred. The landslide, approximately $8.5x10^7$ m^3, is continuously deforming and poses great hazard to life and properties near the populated area. In order to investigate three-dimensional structures and possible internal fractures of the Xishancun Landslide, we deployed a dense seismic array consisting of 20 broadband seismometers and 6 short-period sensors for two weeks. Seismic approaches include thickness of the sediment and identification and relocation of seismic events related to its internal ruptures. After examining the whole dataset, we indentified two types of events. Type I event has duration of more than 100 s. Spectrograms show that this event has energy coming from 10~100 Hz, which suggest that it is probably very close to the landslide. Type II event has a shorter duration of about 2 s and clear P-wave offset. Spectrogram of this event has energy mostly at 10~60 Hz. These two types of events might have different mechanisms. We then used 3-component waveforms of these two events as templates and scan the whole 3-component records using the sliding-window cross-correlation method. We found 4 more Type II events, which occurred on 2~3 November 2013. Relocations of these two types of events indicate that the Type I event occurred at the halfway up the landslide and Type II events are nearly the same location at the foothill of the landslide.

IASPEI (Seismology, Geophysics)

S05a - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-1829

Rupture process of the 2014 Iquique, Chile earthquake estimated from tsunami waveforms, teleseismic body waves, and GPS data.

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We applied a new method to compute tsunami Green's functions for slip inversion of the 1 April 2014 Iquique earthquake using both near-field and far-field tsunami waveforms. Inclusion of the effects of the elastic loading of seafloor, compressibility of seawater, and the geopotential variation in the computed Green's functions reproduced the tsunami travel-time delay relative to long-wave simulation, and allowed us to use far-field records in tsunami waveform inversion. We also used GPS data for a joint inversion of tsunami waveforms and co-seismic crustal deformation. The major slip region with a size of 100 km × 40 km is located down-dip the epicenter at depth ~28 km, regardless of assumed rupture velocities. The total seismic moment from the slip distribution estimated by the joint inversion is 1.24×10^{21} Nm (Mw 8.0). This seismic moment is slightly smaller than 1.88×10^{21} Nm (Mw 8.1) from a teleseismic waveform inversion.

The teleseismic inversion with different rupture velocities (1.5, 2.0, and 2.5 km/s) yielded similar moment rate functions which all peaked at ~35 s, but their spatial slip distributions are different. On the contrary, the joint inversion gives a stable spatial slip distribution for different rupture velocities. Amongst the slip distributions from the teleseismic inversions with the three different rupture velocities, the one for 1.5 km/s is most similar to the slip distribution from the joint inversion of tsunami waveforms and GPS data in terms of large slip area. Thus, the velocity of 1.5 km/s may represent the rupture process of the 2014 Iquique earthquake.

IASPEI (Seismology, Geophysics)

S05a - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-2971

Dynamic rupture simulations constrained by experimental data to understand the rupture process of mega-thrust earthquakes

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The recent inter-plate mega-thrust (M9 class) earthquakes, such as the 2011 Off the Pacific Coast of Tohoku earthquake (Mw 9.0), the 2010 Maule, Chile earthquake (Mw 8.8), and the 2004 Sumatra earthquake (Mw 9.2), revealed that the rupture processes of these M9 class earthquakes are much more complex than expected from extrapolations of kinematic models of M7 class earthquakes. This indicates that our current knowledge is insufficient and further investigations are necessary to understand the rupture process of M9 class earthquakes. We have carried out the simulation of the rupture process of these earthquakes based on dynamic rupture models, in which slip on the fault plane is represented as a spontaneous consequence of seismic faulting governed by the slip-dependent friction law (Ida, 1972).
For the simulation, we used the 3D Spectral Element Method (Galvez et al., 2013) that is stably applicable even for a model with low dipping angle such as a subduction inter-plate earthquake. The friction parameters are set based on experimental data from samples collected at plate boundaries such as the Japan Trench or Nankai Trough etc. (Hirono et al., 2015). Incorporating the features of these experimental data into the simulation allows us to model the rupture process more quantitatively and the results of these simulations are useful to understand and to model the rupture process even for future mega-thrust earthquakes.

IASPEI (Seismology, Geophysics)

S05a - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-3301

Preparation phase and consequences of large earthquakes: a comparative analysis of foreshocks and aftershocks of the 2014 Iquique earthquake (Chile)

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The April 1, 2014, Mw 8.1 Iquique (Chile) earthquake was preceded by an anomalous preparation phase, with sporadic seismicity episodes since summer 2013 and a significant increase of seismicity rates and maximal magnitudes in the weeks before the main shock. The optimal regional seismic network in Northern Chile allowed us to carefully investigate precursor seismicity and to compare it to the aftershock sequence, testing models of rupture preparation and strain and stress rotation during an earthquake. The seismological analysis makes use of some recently developed full waveforms based techniques and targets location, seismicity rate mapping, moment tensor inversion and clustering and stress inversion. Results indicate that the foreshocks were spatially clustered in two main regions separated by a low seismicity central region, a spatial distribution well matching the extension of the aftershocks. The ruptures of mainshock and the M 7.6 largest aftershock nucleated within these clusters and propagated to the locked region. Following the main shock, aftershocks are localized at the original spatial clusters, while the central region is locked again. More than 300 moment tensor solutions reveal a dominance of thrust mechanisms, with an orientation consistent with the slab geometry, and no significant spatial or temporal changes of these mechanisms. However, a new family of normal fault mechanisms appears after the mainshock, as observed for larger earthquakes. We infer a stress rotation after the main shock, which suggests that the mainshock effectively reduced more than half of the accumulated deviatoric stress. The evolution of seismicity and stress inversion are compared to those proposed for significant recent large thrust earthquakes.

IASPEI (Seismology, Geophysics)

S05a - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-4017

Rupture process and strong motion radiation of the 2014 Iquique, Northern Chile, earthquake (Mw8.2)

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An Mw8.2 interplate earthquake occurred off the coast of the Northern Chile, 90 km southwest of the city of Iquique, in April 1, 2014. To investigate the rupture process and strong motion generation of the Iquique earthquake, we estimated the kinematic source models from the waveform inversion and back-projection analyses using the near-source strong-motion records provided by University of Chile. In both analyses, we assumed the same rectangular fault plane model whose length and width are 180 km and 135 km, respectively. We set the fault plane geometry and rupture starting point based on Global CMT solution and USGS hypocenter, and used bandpass filtered (0.02-0125Hz) velocity waveforms integrated from acceleration for source inversion. Our slip model is characterized by a large slip area localized 50 km south of the epicenter with a peak slip of 10 m, and a deeper slip area with a peak slip above 2 m located below the coast. The main fault rupture of these areas started 25 s after the initial break generating two distinctive phases observed at most stations. The landward slip area ruptured for about 10 s generating the first impulsive phase, while the off-shore largest slip area ruptured for 20 s creating a longer duration phase observed later. We investigated the high-frequency wave radiation process by applying a back-projection method to envelopes of bandpass filtered acceleration records (5-10 Hz). The high-frequency radiation propagated down-dip towards the coast near Iquique, reaching its maximum value from 30 s to 40 s at a depth of 40 km, far away from the shallow main slip area obtained from low-frequency waveform inversion. Our results suggest a clear depth and frequency dependence of the seismic wave radiation during the Iquique earthquake.

IASPEI (Seismology, Geophysics)

S05a - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-4091

Diversity of the Iquique's aftershocks a clue about the complex rupture process of a Mw 8.1 earthquake

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The aftershocks of the Iquique Mw 8.1 earthquake show a large diversity of focal mechanisms and type of events. The aftershocks were recorded by a large digital network of more than 30 instruments. We relocated and estimated the moment tensors for almost 150 events of magnitude higher than Mw 4.5. Most of the events were interplate reverse fault events with dip angles that are steeper than the interface between Nazca and South-American plates. The strike angle of these events are in good agreement with the NW orientation of the horst and graben structures (> 2000 meters offset) typical of the oceanic Nazca plate at the trench and in the outer riseregion. The main concentration of interplate events Mw > 4.5 are located surrounding rupture zone of Iquique earthquake. Another important group is located above the plate interface, inside the South-American plate showing diverse focal mechanism, similar to the observed during the foreshock sequence.

A remarkable feature of the Iquique earthquake was its nucleation process, during the first 20 seconds of earthquake only released a small fraction of the total seismic energy. The largest release of seismic energy was generated in the southern end of the rupture. We can interpret this process in terms of a simple asperity model, where the boundaries of the rupture are controlled by the plate interface. The areas surrounding the rupture zone present a low plate coupling and a concentration of repeating events. These characteristics suggest that the different dynamic behaviors of the plates interface are controlled by bathymetric features of the subducted Nazca plate.

IASPEI (Seismology, Geophysics)

S05a - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-5308

A Mogi Doughnut preceding the Mw 8.1 2014 Northern Chile earthquake

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A Mogi Doughnut, a term coined by the Japanese seismologist Kiyoo Mogi in the 60s, describes a spatial pattern of pre-seismic activity where a quiet region is surrounded by a ring of unusual high seismic activity. We here show that the 2014 April 2014 M8.1 offshore Iquique earthquake was preceded by such a seismic pattern and that the mainshock asperity ruptured the Doughnut's hole. The Iquique earthquake as well as its pronounced foreshock series and long-term background seismicity was exceptionally well recorded by the Integrated Plate Boundary Observatory Chile (IPOC). We analyse in detail seven years of seismicity and relocate thousands of earthquakes in a 2D velocity model to better constrain depth in the offshore setting. Our results reveal that until two weeks before the earthquake seismicity occurred exclusively down-dip and to the sides of the mainshock asperity, whereas the asperity itself and the region updip remained quiet, probably due to its setting in the stress shadow cast by the strong asperity. The foreshock series commenced with a M6.7 event in the upper plate two weeks before the mainshock. After the upper plate yielded, foreshocks infringed quickly on the megathrust updip of the asperity. In the following two weeks the foreshocks spread such that the Mogi Doughnut got closed, breaking free and further stressing the asperity until its eventual rupture in the M8.1 earthquake.

IASPEI (Seismology, Geophysics)

S05b - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-0558

Seismic source spectra, stress drop and radiated energy, derived from cohesive-zone models of symmetrical and asymmetrical circular and elliptical ruptures

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Large variability of earthquake stress drops and scaled energy has been commonly reported in the literature, but it is difficult to assess how much of this variability is caused by underlying physical source processes rather than simply observational uncertainties. Here, we examine a variety of dynamically realistic rupture scenarios for circular and elliptical faults and investigate to what extent the variability in seismically estimated stress drops and scaled energy comes from differences in source geometry, rupture directivity, and rupture speeds. We numerically simulate earthquake source scenarios using a cohesive-zone model with the small-scale yielding limit, where the solution approaches a singular crack model with spontaneous healing of slip. Compared to symmetrical circular source models, asymmetrical models result in larger variability of estimated corner frequencies and scaled energy over the focal sphere. The general behavior of the spherical averages of corner frequencies and scaled energy in the subshear regime extends to the supershear regime, although shear Mach waves generated by the propagation of supershear rupture lead to much higher corner-frequency and scaled-energy estimates locally. Our results suggest that at least a factor of two difference in the spherical average of corner frequencies is expected in observational studies simply from variability in source characteristics almost independent of the actual stress drops, translating into a factor of eight difference in estimated stress drops. Furthermore, radiation efficiency estimates derived from observed seismic spectra should not be directly interpreted as describing rupture properties unless there are independent constraints on rupture speed and geometry.

IASPEI (Seismology, Geophysics)

S05b - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-2969

Dynamic rupture simulation of roughness fault by curved grid finite-difference method

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Observations have proved that the surface of fault plane is not exactly planar. Apart from the well known fault kink, branch, there is roughness on fault plane with different characteristic lengths. Due to the irregular roughness surface, initial normal and shear stress of the fault plane are heterogeneous as a homogeneous tectonic stress field is considered. Adding with the geometrical effect on dynamic rupture, the propagation of spontaneous rupture on roughness surface generates heterogeneous rupture patterns, and then radiates high frequency seismic wave. The high frequency seismic wave radiations bring huge devastation to buildings, especially at the near field away from the rupture fault.
In this research, the dynamic rupture on roughness fault is investigated by curved grid finite-difference method (CG-FDM) modeling, which constructs curvilinear grid along the roughness surface and represents the fault discontinuity with split nodes. Numerical simulations suggest that roughness fault surface plays important roles in generating high frequency rupture patterns and seismic wave radiating. With more details, the rupture time as well as the final slip on fault are no longer as homogeneous as for the case of planar fault with same other parameters except different fault surfaces. Rupture on roughness fault may be depressed or promoted due the local gradient of fault surface, with high frequency seismic wave radiating.

IASPEI (Seismology, Geophysics)

S05b - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-4831

An effect of source rupture kinematics on ground motion prediction equations

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Among various effects of source rupture kinematics on seismic ground motion, the hanging wall effect is one of the most accepted ones. Observed ground motions on the hanging walls of earthquake faults are mostly larger than expected from a standard ground motion prediction equation (GMPE). We first examined the effect not only in ground motions observed during crustal earthquakes in Japan and California, but also in those simulated for hypothetical crustal earthquakes. From these examinations, we assumed the hanging wall effect to be caused by fault geometry and rupture heterogeneities. We then revised the GMPEs through two approaches: (1) modifying ground motion attenuation curves for hanging wall ground motions, and (2) introducing a new definition of distance to include the hanging wall effect. The distance in the latter approach is not measured along the shortest path from a site to a fault plane like “fault distance,” but along the shortest path to the horizontal line through the center of a fault plane. This line on a rectangle is called “median” and a main asperity radiating large seismic energy is often located around the median of a fault plane, so that we call the new distance “median distance.” The former approach requires knowing which data are on hanging walls, but the latter does not because the hanging wall effect is already included in the GMPEs.

IASPEI (Seismology, Geophysics)

S05c - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-3020

Evolution of rupture style with total fault displacement: Insight from meter-scale direct shear experiments

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We report results with Indian Gabbro (Vs = 3.62 km/s) that are obtained from a series of meter-scale direct shear experiments conducted at NIED. We focus on strain gage array data of stick-slip events loaded with 0.01 mm/s and under 6.7 MPa normal stress, and find the following: (1) During early stage when the contact surface is relatively intact, ruptures mainly behave as slow-slip events (10 to 100 m/s). (2) With the accumulation of total fault displacement, grooves indicative of strongly coupled local patches (i.e. asperities) are generated along the sliding surface, which are primarily elongated along the loading direction and are accompanied by notable gouge formation. The rest part of the surface continues being polished, indicated by a contrast in light reflectivity with respect to the initial level. At this stage, rupture speeds start to increase but are still well below the shear wave speed (~ 1/4Vs). (3) After long enough total fault displacement (> 500 mm), grooves and gouges of a sufficient amount are generated. The corresponding ruptures show, following a slow nucleation phase, fast propagation with speed comparable to the shear wave speed. Detailed strain data analysis shows that the above rupture style evolution is associated with an increasing efficiency in releasing the accumulated strain on the synthetic fault, which may have been facilitated by powder lubrication (Reches and Lockner, 2010) only after the formation of certain amount of gouges. Our study highlights the role of (evolving) fault surface properties in controlling propagation style of dynamic ruptures. It also calls for the need to conduct large-scale friction experiments over long displacement to better approximate natural fault conditions.

IASPEI (Seismology, Geophysics)

S05c - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-3650

Premonitory activity, rupture speed, radiation pattern and energy budget during stick-slip experiment in Westerly granite

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Since the proposal by Brace and Byerlee [1966] that the mechanism of stick-slip is similar to earthquake mechanics, many experimental studies have been conducted in order to improve the understanding of earthquakes. Here we report macroscopic stick-slip events in saw-cut Westerly granite samples deformed under controlled upper crustal stress conditions in the laboratory.

Experiments were conducted under triaxial loading at confining pressures ranging from 10 to 100 MPa. Using a dual gain system, a high frequency acoustic monitoring array recorded particle acceleration during macroscopic stick-slip events and premonitory background microseismicity.

For the first time, we also record the stress drop dynamically, and we show that the dynamic stress drop, measured locally close to the fault plane, is almost total $\mu d<0.15$ in the breakdown zone, while the strength recovers to values of $\mu>0.4$ within a few hundred of microseconds only. We demonstrate that the frictional behavior during stick-slip follows a slip-weakening law. The increase of the stress intensity factor of the experimental fault with the normal stress acting on the fault plane allows the activation of enhanced dynamic weakening mechanisms, which are well explained by flash heating theory and in agreement with our post-mortem microstructural analysis. Relationships between initial state of stress, rupture velocities, stress drop and energy budget suggest that at high normal stress (i.e. at supershear velocities), the rupture processes become more dispersive. This result seems in agreement with linear elastic fracture mechanics theory and with seismological observations.

IASPEI (Seismology, Geophysics)

S05c - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-5031

Laboratory clues on earthquake friction and fracture energy

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Fault rocks weaken abruptly during seismic slip and show lubrication, interpreted as the effect of thermally triggered physico-chemical processes. Recent experiments systematically explore rock friction under crustal earthquake conditions (slip rate 1-6 m/s, normal stress 5-50 MPa, water pressure or dry, various lithologies). The evolution during experiments is confronted to various thermal weakening models: flash weakening (FW), superplastic diffusion creep, melt lubrication (ML), fluid pressurization (FP). Our findings are that in the absence of melting and/or pressurization (e.g., dry carbonatic rocks) the whole frictional hysteresis cycle is explained by FW of contact asperities, provided that the interface temperature is accurately computed including the effect of heat sinks (latent heat of phase transitions), in a revised version of the FW model proposed by Archard (1958) and Rice (2006). In silicatic rocks under coseismic conditions, initial flash-weakening is followed by melting and subsequently behaves compatibly with the ML of Nielsen et al. (2008, 2010). The effects of water pore pressure on the mechanical evolution vary subtly depending on lithology and amount of sliding. However, experiments performed in the presence of water seem to indicate that thermal pressurization is not the dominant dynamic weakening mechanism as other thermal weakening act earlier and more efficiently. Frictional work in excess of minimum dynamic level, obtained in a number of experiment, yield values comparable to estimates from earthquake data for slips up to about u=1cm (~10^4 J/m^2), to increase gradually with slip up to about 10^6 J/m^2. However, it appears that earthquake fracture energy estimates are is slightly larger than the laboratory measures in the range of slip 0.1<u<10.< p=""></u<10.<>

IASPEI (Seismology, Geophysics)

S05c - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-5446

Rupture Phase Diagram for a planar fault in 3D full space and half space

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In this study, we have systematically investigated the in?uence of parameters of slip-weakening law and size of nucleation asperity on dynamic rupture of a planar fault in full space and half space using boundary integral equation method, in particular, the occurrence conditions for subshear (or sub-Rayleigh for strike-slip rupture) and supershear ruptures. Besides the well-known rupture styles of subshear (or sub-Rayleigh) and supershear, we de?ned a new kind of rupture style in this study, termed the Self-Arresting Rupture for which the rupture process can be autonomously arrested by itself without any outside interference (e.g., a high strength barrier). Based on the vast number of simulations, we obtained rupture phase diagrams for strike-slip and dip-slip ruptures vertically and obliquely embedded in full and half spaces with different buried depths. The rupture phase diagram clearly illustrates the occurrence conditions of three kinds of rupture styles and transitions between them. In full space, supershear condition for a 3D strike-slip rupture is different from that for a 2D in-plane rupture and it shows more complicated features. However, at limit of Dc/Ra = 0, both results are identical. Owing to the in?uence of free surface, rupture in half space becomes much more complicated comparing to the one in full space. For a strike-slip fault with zero buried depth, all ruptures that occur within the parameter range for sub-Rayleigh ruptures in full space case become supershear ruptures. Although the in?uence of free surface is strong, it is limited to very shallow ruptures (i.e., buried depth < 1km). The rupture phase diagram discussed in this work could provide us a new insight on earthquake rupture mechanics.

IASPEI (Seismology, Geophysics)

S05c - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-5719

The nucleation and dynamic rupture of laboratory earthquakes

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We present the results of dynamic rupture experiments intended to mimic seismic rupture of faults. The experimental device consists of a plate of polycarbonate in which a fault is cut at a critical angle, such that it produces stick-slip when it is submitted to uniaxal stress loading. The ruptures are visualized by photo-elasticity recorded with a high velocity camera. The radiated wavefield is studied with a network of acoustic sensors. In a first part, we study the slow initiation of the rupture. We show that this stage actually consists of two phases, a long exponential growth followed by a catastrophic acceleration. The critical length and critical rupture velocity of the transition scale depend inversely on the normal stress; while the characteristic time is independent of the normal stress. We discuss these results with respect to recent observations of earthquake nucleation in natural faults. In a second part, we will show that this experiment can be used to study the effect of barriers on a fault, as well as the effect on rupture propagation of a kink on a fault. We provide detailed observation of the wavefield radiated by the barrier, and compare it to the wavefield radiated by a kink. We compare the observations with theoretical results for the radiation of a barrier in a 2D in-plane geometry, and with 2D numerical simulations of rupture dynamics by the spectral element method.

IASPEI (Seismology, Geophysics)

S05d - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-0260

State of tectonic stress and b-value structure before and after the 2004 Andaman-Sumatra mega earthquake Mw 9.3

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Centroid Moment Tensor (CMT) solutions of some 1239 earthquakes Mw > 5.0 in the Andaman-Sumatra-Java subduction zone are used for inversion analysis to examine the state of tectonic stress before and after the 2004 tsunamigenic mega thrust earthquake Mw 9.3. Some 348 CMT solutions before (during 1976 - December, 2004) and 891 solutions after (during December, 2004 - 2008) the mega event were available. We subdivided the region into three tectonic blocks: Andaman-Nicobar, Sumatra and Java. Dramatic changes of orientation of the maximum and intermediate stress axes have been observed in the Sumatra region after a large earthquake Mw 7.3 in 2002. This change may be attributed to a precursor (?) phenomena for the December, 2004 mega event. After the 2004 mega event, followed by the 2005 great event Mw 8.7 in this region, orientation of the two stress axes returned to the original position as they were before the 2002 large event.

Some 8,000 relocated earthquakes, including more than 3,000 aftershocks (M > 4.5) of the 2004 earthquake, recorded during the period 1964–2007 are used to estimate b-value, frequency-magnitude relation.The b-value maps and cross sections show spatial as well as depth variations all along the Andaman-Sumatra subduction zone. Significant spatial changes in b-value, before and after the 2004 mega earthquake, are observed. In cross sections, the major tectonic features, like the oceanic trench and the back arc spreading zone (Andaman Sea Ridge) are well imaged as a higher b-value or less stressed and the subducted dipping slab as a lower b-value or more stressed structures.

IASPEI (Seismology, Geophysics)

S05d - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-0280

Modified Friction Law and Non-Linear Geodynamical analysis of rock failure

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It is established fact that the strength of the earth's crust is based on a simple model that utilizes the friction law of rocks in the shallower or 'brittle' layer of the crust and the plastic flow law in the deeper or 'ductile' layer. Faulting and sliding on frictional surface is the primary mode of deformation in the upper lithosphere. A wide deformation conditions are possible and these must be examined to realize earthquake source processes and factors that control lithospheric strength. It is well apparent that the failure envelope for rocks is not straight line but curvilinear and concave towards the normal stress axis. It is proposed in this paper that the critical state of rock should be a part of the non-linearity of the strength criterion. A simple parabolic strength criterion is proposed and the critical state is assumed at the confining pressure equal to the UCS of the rock material or as found experimentally. The coefficient of internal friction (mu) , which is the gradient of the failure surface, is observed to be varying non-linearly from a value of (muo), in unconfined state, to about zero in the critical state. Plots have been presented to assess m at any given confining pressure (sigma(3)). The plots are also drawn against the non-dimensional parameter (sigma(3)/sigma(ci)) and are found to be independent of the UCS of the rock, therefore, may be used for all rock types in the non-linear geodynamical or any other analysis. A mathematical expression has also been derived and suggested to compute m accurately at any confining pressure. The modified friction law will improve our understanding of the non-linear geodynamics.

IASPEI (Seismology, Geophysics)

S05d - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-1961

Fault Slip Model of 2013 Lushan Earthquake Retrieved Based on GPS Coseismic Displacements

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Lushan earthquake (~Mw6.6) occurred in Sichuan Province of China on 20 April 2013, was the largest earthquake in Longmen Shan Fault Belt since 2008 Wenchuan earthquake. To better understand its rupture pattern, we performed fault slip inversion using Akaike's Bayesian Information Criterion (ABIC) method. Based on GPS coseismic data, our inverted results showed that the fault slip is weak and mainly confined at depths. The maximum slip amplitude is about 0.7m, and the scalar seismic moment is about 9.47×10^{18}N·m. Slip pattern reveals that the earthquake occurred on the thrust fault with large dip-slip and small strike-slip, such a simple fault slip represents no second sub-event occurred. The coulomb stress changes (DCFF) matched the most aftershocks with negative anomalies. The inverted results demonstrated that the source parameters have significant impacts on fault slip distribution, especially on the slip direction and maximum displacement.

IASPEI (Seismology, Geophysics)

S05d - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-3522

Ten year recurrence time between two major earthquakes affecting the same fault segment

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Earthquake ruptures stop when they encounter barriers impeding further propagation. These barriers can theoretically originate from changes of geometry or nature of the seismic faults or from a strong lowering of the tectonic stresses, typically due to the occurrence of a recent major earthquake. We show here, based on the seismological analysis of a large earthquakes pair occurring in 2003 and 2013 along the Scotia-Antarctic plate boundary, that this latter mechanism can be ineffective at stopping rupture expansion. Aftershock locations, backpropagation techniques, and source inversion consistently show that the 17 November 2013 magnitude 7.8 Scotia Sea earthquake has propagated into a 100 km long zone already ruptured by the 4 August 2003 magnitude 7.6 earthquake. Given the plate velocities between Scotia and Antarctic plates (8–9 mm/yr), simple recurrence models would have predicted that the segment affected by the 2003 earthquake could not be re-ruptured by a major earthquake during several hundreds of years. This earthquake pair indicates that the variations of the tectonic stress during the seismic history of the fault are small compared to the stresses dynamically generated by a large earthquake.

IASPEI (Seismology, Geophysics)

S05d - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-3585

Seismological evidences of conjugated ruptures of the 2014 Ludian MW6.1 earthquake

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On August 3, 2014, a moderate earthquake of M_W6.1(M_S6.5) occurred in Ludian, Yunnan province of China. Though it was moderate in magnitude, the quake caused tremendous disaster in the meizoseismal area of intensity IX in Chinese Intensity Scale. It caused 618 deaths and injured 3143 people, and 112 people were reported missing. About 25.8 thousands houses were destroyed and 40.6 thousands houses badly damaged. To explore the seismological cause of tremendous disaster of the Ludian earthquake, the focal mechanism and the source rupture process were studied using several kinds of seismic observation data. The joint inversion of strong ground motion recordings, local seismic and teleseismic data shows that the Ludian earthquake rupture very possible associated with two conjugated faults which strike NNW-SSE and ENE-WSW, respectively. The ruptures initiated on the ENE-WSW striking, right-lateral strike-slip fault in the first two seconds, and then triggered the NNW-SSE striking, left-lateral strike-slip fault on which most seismic moments released. The total rupture duration time is about 17s, but most seismic moments were released in the first 10 s after the rupture initiation. While the ENE-WSW striking fault rupture mainly propagated towards up-dip direction, the NNW-SSE striking fault rupture mainly propagated both up-dip and southwards. The slip-concentrated patches of the two conjugated faults mainly occurred in very shallow depths, which may account for the tremendous seismic disaster in the meizoseismal area. The relocated aftershocks provide independent seismological evidence that the geometry of hypocentral distribution of the Ludian aftershocks sequence may also be accounted by the two conjugated faults rupturing pattern of the Ludian earthquake.

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S05e - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-0695

Toward rapid source process analysis for great earthquake using teleseismic body waves: Problems of Green's functions based on ray theory

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Source processes for great earthquakes are now obtained in near-real-time by teleseismic body wave analyses. Green’s functions of most teleseismic body waves analyses are based on ray theoretical method, but such methods have the following two problems for great earthquakes source process analyses: difficulty in calculating all later phases such as PP waves and impossibility of calculating very long period phase called a W phase. To solve these problems, we introduced the complete Green’s functions (i.e., all body and surface waves) calculated by Direct Solution Method. We show that source process analyses results of 2011 Tohoku-Oki earthquake (Mw7.3), 2007 Solomon earthquake (Mw8.1), and 2010 Chile earthquake (Mw8.8) using the complete Green’s functions. We also analyzed these earthquakes using the conventional ray theoretical Green’s functions in order to make clear the problems of ray theoretical method. The obtained 2011 Tohoku-Oki earthquake source process using complete Green’s functions is not so different from that of using ray theoretical Green’s functions. However, the source process of 2007 Solomon and 2010 Chile earthquake using conventional ray theoretical Green’s functions are quite different especially later part of source process compared with that of using the complete Green’s functions. These difference mainly caused by neglecting W phase of the ray theoretical Green’s functions calculation. When you analyze the great earthquake in near-real-time using ray theoretical Green’s functions, we recommend that you should be use the station of small amplitude W phase as much as possible and may be better use velocity observed seismograms rather than displacement observed seismograms.

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S05e - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

IUGG-2285

The Cephalonia 2014 earthquake sequence – what is certain and uncertain?

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The January/February 2014 earthquake sequence that occurred at Cephalonia Island comprised two damaging Mw 6+ events. Several papers have been already published, however we show that many source parameters remain uncertain. The absolute location of the first strong event (Jan 26) based on Greek stations is hampered by azimuthal gap and the inclusion of (distant) Italian stations is difficult due to inaccurate knowledge of the velocity model. The location of the second strong event (Feb 3) is better constrained by the local temporary network. Its hypocenter is shallower compared to the Jan 26 event and shifted towards NNE. Relative locations of the entire sequence provide a diffuse pattern with no indication of distinct fault planes. Determination of centroid position from near-regional waveform inversion has similar problems as the absolute location. Nevertheless, five local stations enabled slip inversion of the Jan 26 event (< 0.2 Hz). The fault plane location and mechanism were fine-tuned by grid search. A smaller subevent, delayed by ~6s, is shifted ~20km along strike. The Feb 3 event is definitely more complex and involves perhaps at least two fault segments. Although the activated faults seem to be constrained by InSAR data (Boncori et al. 2015), there is always a possibility that the data contain signal from post-seismic motion. We provide alternative hypothetical models of the Feb 3 event consisting of two fault planes. The complexity explains the large observed non-DC component. Opposed to difficulty with the main events, local stress field is well resolved. The variety of aftershocks enables stress inversion confirming the predominantly strike-slip regime of the region (sigma 1 horizontal, azimuth 250°; sigma 2 almost vertical).

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IUGG-2944

Rupture dynamics inferred from early stage of the 2011 great Tohoku-oki earthquake

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The occurrence of the 2011 M 9.0, Japan, Tohoku-oki earthquake gives us a unique opportunity to investigate the detailed process of the initiation and propagation of a rupture during a gigantic earthquake. It is observed that the mainshock of the Tohoku-oki earthquake was triggered by the M7 foreshock with time delay of two days occurred near the hypocenter of the mainshock. Therefore, it is expected that the early stage of the mainshock rupture reflects perturbations caused by the foreshock. In order to test this hypothesis, we examine the stress changes during the dynamic rupture propagation of this event. We used the kinematically inverted slip profile obtained by Uchide (2013), JGR, which conducted the multi-scale seismic slip inversion focusing on the first few ten seconds of the mainshock; he showed that the slip profiles around the hypocenter exhibited high-speed rupture propagations. We calculate the dynamic stress changes on the fault plane given the inverted slip profile by applying the 3-D elasto-dynamic boundary integral equation method (Ando and Okuyama, 2010, GRL). The calculated stress changes shows generally the slip weakening behavior consistent with the occurrence of the high speed rupture. The obtained stress change also shows heterogeneous distribution over the fault area, which might reflect the stress perturbation existed before the mainshock.

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IUGG-4211

Dynamic stress drop for mining induced events

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In this contribution we report our results on the dynamic stress drop calculations - the quantity describing frictional forces at a slipping fault plane during the unstable part of the earthquake. The calculation are based on the analysis of the source time function estimated through the Empirical Green Function approach using seismic data recorded by underground seismic network operating in the Rudna (Poland) copper mine. For 32 analyzed events with magnitude range 2.5 - 3.5 the dynamic stress drop does not clearly correlate with any physical parameter characterizing the rupture processes but only with rupture velocity. We have found that the dynamic stress drop is statistically larger for faster events than for slower ones. This observation suggests thus that among high speed rupture processes the overshooting rupture mechanisms seems to be preferable.

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IUGG-5145

Effects of mid-ocean ridge transform fault segmentation on earthquake behavior

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Observations of changes in seismicity along strike and with depth on Discovery and Gofar mid-ocean ridge transform faults (RTFs) on the East Pacific Rise (EPR) suggest segmentation in fault zone properties may control rupture kinematics and dynamics on these faults. Here we combine results from spectral analysis of ocean bottom seismic data, finite element modeling of fault thermal structure, and bathymetric data to investigate the role of fault properties on the rupture of RTF earthquakes. Specifically, we employ an empirical Green's function technique to determine if stress drops of moderate sized earthquakes, $3.0 \leq Mw \leq 5.5$, on Gofar transform fault vary between rupture patches and rupture barriers. Initial results show higher average stress drops of ~2 MPa in rupture patches compared with ~1 MPa in rupture barriers. Secondly, we conduct three dimensional finite element modeling to determine the effect of short intra transform spreading centers (ITSCs) and realistic rheology on fault thermal structure. We develop a scaling relation for fault area that incorporates the ITSCs, such that given kinematic fault parameters (segment lengths and slip rate), the total area above 600°C can be predicted. On fast slipping EPR faults, we find that an ITSC of 2 km or longer will significantly reduce the seismogenic fault area. Furthermore the change in fault trace will alter the stress field and may lead to enhanced fluid circulation and possibly velocity-strengthening frictional conditions, as is suspected on Discovery and Gofar RTFs. Finally, we compare our thermal modeling results to surface fault traces derived from bathymetric data for ~200 fault segments to investigate whether detailed fault structure can explain the maximum magnitudes of RTF earthquakes.

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S05p - S05 Source Rupture Kinematics and Dynamics: Observation and Inversion

S05p-365

Relationships between second and third corner frequencies of earthquake source spectra as determined from P and S waves

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Parameters of earthquake source spectra as manifested in recorded P and S spectra are important for earthquake source physics. The relationship between common (first) corner frequencies, fc1, of P and S waves has been widely studied. Similar relationships are in essence unknown however for second, fc2, corner and third, fc3, corner frequencies. fc2 and fc3 are defined here as the lower and the upper cutoff frequencies of source acceleration spectrum. Whereas the existence of fc2 is relatively well established, the reality of fc3, better known as 'source-controlled f-max', is disputable. To determine corner frequencies, source spectra of more than 400 earthquakes has been determined in the frequency range 0.5–30 Hz using digital records of 8 rock-ground Kamchatka stations, using 3 or more records per event. The range of magnitudes is 3.0– 6.8, the range of hypocentral distances is 50–250 km. To enable reduction of a recorded spectrum to the source, loss parameters QP(f) and QS(f) were estimated beforehand. In many cases, the third spectral corner can be identified, and fc3 can be picked. Coefficients of variation (relative rms scatter) among several single-station estimates of fc2 and fc3 for the same earthquake were estimated. Averages over these are around 0.2 or lower. The estimates of fc1, fc2 and fc3 from P and S waves were compared, with the following results: (1) On the background of considerable scatter, fc1, fc2 and fc3 from P waves and those from S waves are proportional to one another (respectively). (2) The average ratio fc1(P)/fc1(S) is about 1.25, as commonly found. (3) The average ratio fc2(P)/fc2(S) is comparable, about 1.30. (4) The average ratio fc3(P)/fc3(S) is about 1.15. Possible meaning of these figures will be discussed.

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S05p-366

Equivalent body force finite elements method and 3d earth model applied in 2004 Sumatra Earthquake

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We use equivalent body force finite elements method and mesh the whole earth, to compute global co-seismic displacements using four fault slip models of the 2004 Sumatra earthquake provided by different authors. Comparisons of calculated co-seismic displacements and GPS show that the confidences are well in near field for four models, and the confidences are according to different models. In the whole four models, the Chlieh model (Chlieh et al., 2007) is the best. The effects of data used in inversion, the geometrical model and the earthquake model are discussed in this paper. For great earthquake, the reasonability of co-seismic displacements is one justification of evaluating the fault slip model. The vertical displacement is less sensitive to the fault slip model.

We also use Crust1.0 3D earth model to calculate the seismic dislocation. The effect of the 3D earth model is about 40 per cent compared with the PREM spherical symmetrical earth model.

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S05p-367

FEM simulation of dynamic processes of fault spontaneous rupture

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This study first improved classical slip-weakening friction law, and then used the finite element method performing simulation. In order to explore rupture propagation on fault surface, we construct two different model geometries: the first case has only one fault, the other includes stepover which consists of two faults.

In the case of one fault, the computed results demonstrate that pulse-like rupture is possible by modifying classical slip-weakening friction law, but it is impossible with the classical slip-weakening friction law. It also shows that the behavior of the fault spontaneous rupture process is affected by the initial stress field and the friction law. When the initial shear stress is low, it is easier to generate pulse-like rupture. But it is a crack-like rupture when initial shear stress is in high level. This is consistent with the laboratory result of small-scale rock rupture. With the same initial stress, fault tends to produce pulse-like rupture with large dynamic friction coefficient and crack-like rupture with small dynamic friction coefficient.

In the study of rupture propagation through stepover, the simulated results confirm previous investigations. Moreover, we found that it requires a time delay between the rupture front reaching the end of the causative fault and the initiating rupture on the triggered fault. This delay time period is decided by the stepover geometry, frictional law, initial stress, and fault materials.

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S05p-368

A new fast full waveform moment tensor inversion for microseismic monitoring

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The moment tensor inversion of microseismic, which is a good way to understanding the fracturing process, has gained increasing popularity in recent years. Especially, some nonlinear focal mechanism inversion methods have been developed in recent years. However, directly inversing the moment tensor is just a linear problem. Moreover, the Generalized Reflection and Transmission method (GRT) is a fast and high efficient method for calculating full wave fields in the layered medium. We optimized the procedure of GRT method to improve the computation efficiency of Green functions, and then developed a new linear fast full-waveform moment tensor inversion method for microseismic monitoring. Because there are no constraints in the inversion, the moment tensor can contain some non-double couple components. Therefore, a new way modified from traditional way to obtain source parameters has been introduced. Finally, in order to check the reliability and robustness of the new method, we investigate the influence of velocity model errors, data noise and stations distribution on the inversed source parameters. The synthetic tests showed that our method is robust and efficient even when noise level is up to 50% or the velocity model errors is less than 20%. Moreover, the better the azimuth coverage is, the more robust the moment tensor inversion.

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S05p-369

Popperian extended fault inversion with random slipmaps: resolution test for the 2012 Nicoya (Costa Rica) and 2011 Lorca (Spain) earthquakes.

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We present and apply a strategy to evaluate the resolution problem and to explore ambiguities in finite or extended fault inversions. We use a global search technique that scans the solutions domain using random slipmaps. First, heterogeneous slip distributions are generated assuming a von Karman autocorrelation function, keeping the rake angle, rupture velocity and slip velocity function fixed. A control test is carried out to estimate the solutions domain size, usually around 10.000 models. Then, we compute their forward predictions and falsify inappropriate trial models that do not reproduce the data within a reasonable level of mismodelling. Therefore, this Popperian inversion strategy involves generating a set of coequal solutions through falsification. The effectiveness of the method has been verified by applying the results to teleseismic (2012 Mw 7.6 Nicoya) and regional data (2011 Mw 5.2 mainshock and Mw 4.6 foreshock Lorca earthquakes). For a solution set, a classification of slipmaps according to any appropriate similarity may help us to interpret the inversion result and to propose different hypotheses for the source process. Thus, we can evaluate the resolution identifying potential slipmap families. The Nicoya solution set consistently shows a single dominant slip patch around the hypocentre from 50 teleseismic body-waves. Uncertainties are related to the details of the slip maximum and the characteristics of peripheral slip. On the other hand, rupture directivity resolution is assessed for the Lorca earthquakes adjusting Apparent Source Time Functions. The two events show one asperity located SW of the hypocenter towards the town of Lorca.

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S05p-370

Uncertainty of Green functions for waveform-based earthquake source inversions

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Green functions (GFs) are an essential ingredient in waveform-based earthquake source inversions. Hence, their error due to imprecise knowledge of a crustal model is the major source of uncertainty of the inferred earthquake source parameters. Strategies how to incorporate the modeling error (uncertainty) of the GFs in waveform inversions have been recently introduced (e.g., Yagi and Fukahata, 2011; Duputel et al., 2014). They rely on statistical description of the GFs uncertainty by means of the covariance matrix properties, of which is the topic of our study. We evaluate uncertainties of GFs by series of Monte Carlo simulations of GFs in randomly perturbed 1D crustal model. Then, the uncertainty of the GFs is described by the Covariance Function (CF) averaged over time. We analyze the dependence of the resulting CF on the strength of the crustal model perturbations, receiver-source distances, and frequency ranges. We show that the major effect of the perturbed crustal model is a temporal shift of the simulated waveforms. Furthermore, under the assumption of pure time shift with uniform time-delay distribution we derive a simple analytical formula for the CF. The analytical formula, which may be easily implemented in the inversion techniques, exhibits very good agreement with the CF obtained by the Monte Carlo simulations.

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S05p-371

Shock waves as the cause of abnormally high PGA observed during the 2011 Tohoku earthquake

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During the 2011 Tohoku earthquake (Mw=9.0) nineteen stations recorded abnormally high peak accelerations exceeding 1g, the highest reaching ~3g. Based on records of vertical arrays Kik-net, we studied soil behavior during the Tohoku earthquake and revealed its ‘atypical’ pattern: instead of being reduced in the near-source zones as usually observed during strong earthquakes, shear moduli in soil layers increased, indicating soil hardening, and reached their maxima at the moments of the highest intensity of strong motion, then reduced. We could ex-plain this assuming that soils experienced some additional compression, caused by a certain factor. The observed changes in the shapes of acceleration time histories with distance from the source, such as, decrease in the duration and increase in the intensity of strong motion, lead us to the conclusion that a shock wave occurred during the Tohoku earthquake, compressed the soils and produced the observed high peak accelerations on the surface.

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S05p-372

New insights on seismogeneric structures in southwest Taiwan after the 1999 Chi-Chi earthquake sequence: Implications from spatial-temporal variations of b-value

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The b-value derived from the Gutenberg-Richter relation has been playing an important role in indicating effective stress level and degree of heterogeneity of medium in various tectonic regimes. The b-value also serves as precursor prior to a strong earthquake. The southwest Taiwan is the foreland of vigorous maintains building, which constitutes a series of complex and active fold-and-thrust belts and the seismic potential in the area is necessarily to be considered. Beside, one of the major active Chukuo Fault is right located in the southern end of the Chelongpu Fault which caused the 1999 Chi-Chi earthquake, and the stress level in the Chukuo Fault zone and nearby fault systems after the occurrence of the Chi-Chi earthquake sequence needs to be carefully examined. The spatial-temporal variations of b-value using seismic catalogue from the Central Weather Bureau, Taiwan, is conducted. Our results show that b-value is clearly depth dependent and the b-value varies from 0.5-0.7 in seismogeneric depth between 7 and 12 km. The spatial distribution of b-value shows that low b-value is in the southeast of the Chukuo Fault and nearby sub-fault systems. However, the area near the Meishan Fault zone that caused the 1906 great M7.1 Meishan earthquake shows relatively higher b-value. Our results also suggest that the b-value exhibits descending trend after the 1999 Chi-Chi earthquake sequences. We also observed that b-value decreased significantly before the occurrence of several moderate earthquakes in the study area. Our results can provide new perspectives in planning local seismic hazard mitigation.

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S05p-373

Period-dependent seismic radiation for the 2011 Tohoku-oki earthquake estimated by multi period-band source modeling

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The source process of the 2011 Tohoku-oki earthquake (M_w 9.1) has predominantly been investigated by source inversions using long-period (10 s-) seismic waveforms and source modeling using short-period (0.1-10 s) seismic waveforms. Based on a comparison of these results, it has been suggested that this event had a period-dependent spatial variation on its seismic-wave radiation (e.g., Ide et al., 2011; Koper et al., 2011). In order to further investigate the period-dependent seismic radiation for this event from a perspective of the generation of broadband seismic motion in the period-band from 5 s to 100 s, we constructs source slip models for the 2011 Tohoku-oki earthquake in multi successive period-bands (5-10 s, 10-25 s, 25-50 s, and 50-100 s) using strong-motion data and the newly-developed kinematic source inversion method which introduces a fully Bayesian method to the multi-time-window method (Kubo et al., 2014). Green's functions are calculated by the FDM (GMS; Aoi & Fujiwara, 1999) with a 3D velocity structure model (JIVSM; Koketsu et al., 2012).

The comparison of the source models for the different period-bands indicates that the shallow off-Miyagi region, which has a huge slip (approximately 30 m), strongly radiated long-period (50-100 s) waves but weakly radiated relatively short-period (5-25 s) waves. In the deep off-Miyagi region, twice ruptures are observed in all the period-bands, indicating that this region radiated not only short period (5-25 s) but also long-period (25-100 s) seismic. In addition, a difference in the dominant period of the seismic-wave radiation between the twice ruptures is discovered. The difference in the rupture extent between the twice ruptures indicates that it was caused by the rupture of the hierarchical asperity.

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S05p-374

Spectral characteristics of seismicity originated in the valley of Mexico

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The major source of seismic hazard for the Valley of Mexico (VM) is the subduction zone of the Pacific coast where the Cocos plate subducts beneath the North America. Historically there have been earthquakes in that area of magnitude up to 8.2. Another element of seismic risk for this zone is the seismicity originated inside, which even of low magnitude ($M<3.5$), is important since this area is the most important region of Mexico from an economical point of view and of population concentration. This work presents an analysis of focal characteristics of seismicity originated at VM, thanks to the records obtained from a seismic broadband network recently installed in this area. Among the earthquakes with epicenter at the VM during the period 2008-2012, the 15 events with the best signal to noise ratio were chosen. We used acceleration signals, and performed a spectral analysis to obtain the seismic moment (M_0), the stress drop ($\Delta\sigma$) and the attenuation factor (t^*). Average values found for $\Delta\sigma$ and t^* were 1.2 MPa and 0.04 s respectively, indicating that this region exhibits high attenuation compared to regions outside. This result is consistent with recent determinations of quality factor Q_0 within the VM, and reinforces the hypothesis that, in general, the center of Mexico is characterized by a rapid decay of the amplitude of the waves with the distance, similar to what occurred in other tectonically active regions.

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S05p-375

Static deformation caused by april 2014 Chile earthquakes

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During March-April 2014 a series of earthquakes occurred around the Iquique city located in the northern Chile region. Static deformation represents the permanent displacement caused by earthquakes. Geological fault movements plus their related stress distributions can be examined by static deformation. Here we estimated vertical and horizontal static displacements due to AK135 velocity model for Mw=8.2, 1 April 2014 and Mw=7.7, 4 April 2014 earthquakes occurred in Chile. For both events we employed finite fault solutions provided by USGS as input file for the simulations. According to the results for Mw=8.2 the maximum deformations are: 159.3 cm upward and about 33 cm downward, 124 cm westward and 4 cm eastward, 85 cm southward and 23 cm northward. For Mw=7.7 maximum deformations are: around 45.6 cm upward and around 10.6 cm downward, 36 cm westward and 1.3 cm eastward, 26.3 cm southward and 5.4 cm northward. Meanwhile the vertical deformation results show that there exist uplift and subsidence along the hypocenteral area of both earthquakes. The maximum of uplifts has been occurred around the epicenter (between the trench and coast) and maximum of subsidence close to the coastal area under the continental north Chile.

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S05p-376

A joint seismic and geodetic rupture model for the 2012 Haida Gwaii earthquake off the coast of British Columbia

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The October 28th, 2012, Mw7.8 Haida Gwaii earthquake occurred off the coast of northern British Columbia, in the transition region between subduction of the Juan de Fuca plate beneath the North American plate to a transform fault between the Pacific plate and North American plate: the Queen Charlotte fault system. In the immediate vicinity of the Haida Gwaii earthquake rupture, relative motion between the North American and Pacific plates is more transpressional in nature than to the North, where the Queen Charlotte Fault System has produced several large (M8+) strike-slip earthquakes. The mechanism of the October 28th, 2012, earthquake is indicative of Pacific plate underthrusting beneath Haida Gwaii, showing slightly oblique thrust faulting on a shallowly dipping plane with a strike parallel to the Queen Charlotte Fault.
We will present the results from a joint kinematic rupture inversion using teleseismic body and surface wave data, and InSAR data. We incorporate two RADARSAT-2 differential interferograms calculated from Wide Swath beam images from left and right-looking operations on two ascending orbital tracks with time intervals of 8-10 months. A third image could not be used in the inversion due to the presence of cycle-skipping artifacts in the interferogram. Our inversions result in a rupture model with a single primary slip region with a width of 100-120 km along trench, from 52.75°N to the South, and a maximum of 8 m of slip. When attempting to constrain the rupture to the shallower part of the subduction interface to the West of the Queen Charlotte Fault, no satisfactory fit can be obtained between data and synthetics. Therefore, our results indicate that the Haida Gwaii earthquake rupture on the interface extended past the Queen Charlotte Fault.

IASPEI (Seismology, Geophysics)

S06a - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-3153

On the nature of the spectral matched signals

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Spectral matched accelerograms are currently used in practical applications to generate time histories compatible with an assigned target spectrum. The main advantage of this approach is that fewer engineering analyses are needed to obtain the same level of accuracy in the response estimates. The main disadvantage is that the response obtained may be systematically biased, as shown by some early work on the subject, because the original accelerograms have been tampered with. The reason why this may be the case, however, has been speculated but not yet proven. Besides the purely engineering viewpoint, from a seismological point of view, some questions arise on the nature of the manipulated records. In this work these questions are addressed following an unconventional strategy: after selecting 296 waveforms the response spectra of real records are used as target spectra to be matched via the computer code RSPMatch. The novelty and the peculiarity of this approach is that each target spectrum has a corresponding waveform making then possible to understand similarities and discrepancies between the real record and the many matched ones. The comparison is performed in terms of commonly used ground motion intensity measures (IMs), such as spectral ordinates and Arias Intensity. The distribution of the IMs measured on each family of matched signal is characterized by a small variability, and in the case of cumulative absolute velocity and Arias intensity, a systematic bias is indeed observed. The spectral coherency analysis highlights some common feature between the matched waveform and the natural one associated with the target spectrum, this is an intriguing result that requires further scrutiny since the waveform is not involved in the matching process.

IASPEI (Seismology, Geophysics)

S06a - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-3787

Strong ground motion record selection; approaches, challenges and prospects

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Nonlinear Time-History Analysis (NLTHA) is one of the most reliable choices to compute the Engineering Demand Parameters (EDPs) and quantify the dynamic response of engineering structures. New generation of seismic guidelines accept the method as an efficient tool, specially, in the case of irregular systems and tall buildings.

The first step in NLTHA is to select a set of ground motions in order to achieve a reliable estimation of desired EDPs. There is a variety of methods suggest the selection, scaling, matching and artificial generation of accelerograms to ensure the compatibility with the design intensity levels. Most of the structural codes and standards use the elastic response spectra as the representative of required seismic risk. The selected ground motions should be scaled up or down to a predefined level of intensity, for example elastic response on the first mode of vibration. It has been shown that the effective selection and scaling of input ground motions can reduce the bias in the dynamic structural response.

Although, Different ground motion selection methods in the earthquake engineering literature have focused on the reduction of computational cost without losing the accuracy, some controversial issues such as the selection and scaling of vertical components, selection of a horizontal pair of components in case of bidirectional analysis, consideration of near-fault characteristics and the influence of the higher modes of vibration are still unresolved. In this paper, an overview of ground motion scaling and selection approaches is presented, while the possible challenges and limitations are investigated both qualitatively and quantitatively. After a comprehensive comparison among the methods, new areas for future research are recommended.

IASPEI (Seismology, Geophysics)

S06a - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-4085

Stability assessment of gmpes for the iranian ground motion database

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Selection of Ground Motion Prediction Equation (GMPE) is one of the key elements within a seismic hazard analysis. The variety of available GMPE models makes this selection a scientific challenge. Therefore, the stability assessment of a set of GMPE models are investigated in this paper by employing the new emerged Re-Sampling Analysis (RSA) methodology (Azarbakht et al. 2014). Four GMPE categories were examined in this paper which are: (1) The local GMPE models which are developed based on Iranian events, (2) Regional GMPE models which are for Europe and Asia, (3) The NGA-WEST1 GMPE models, and (4) The NGA-WEST2 GMPE models. The ground motion database in this study consists of 691 acceleration time series resulted from 85 seismic events. The magnitude range is between 5.0 to 7.4 and all the records have the distance less than 200 km. The RSA results illustrate the bias versus the magnitude, distance measure (Joyner-Boore distance (R_{JB}) is identical to Epicentral distance (R_{epi}) in this study) and shear wave velocity (Vs30).

By given the mentioned points, Rahpeyma et al. (2014) model, a genetic programming based (GP-based) GMPE, as well as Zafarani et al (2012), physical attenuation relationship, show good agreement against different seismic parameters (Mw, R_{JB}, Vs30) with this criteria. In addition, both NGA GMPE groups (NGA-WEST1 and NGA-WEST2) show poor performance based on the RSA results.

IASPEI (Seismology, Geophysics)

S06a - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-4330

Ground motion selection based on a synthetic uniform hazard spectrum

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In this study, synthetic uniform hazard spectrum (UHS) of Erzincan region in Eastern Turkey is derived based on simulated ground motions. Monte Carlo simulation method is used to identify the spatial and temporal distribution of events. The magnitude distribution of events is derived from Gutenberg-Richter recurrence model. The simulations are repeated until a complete catalog is obtained. Ground motion time histories are generated for each event and a specified site. Response spectrum of each time history is then calculated for a proper period range. Annual exceedance rate of each response is obtained from the statistical distribution of the whole response spectra for a single site. Response spectra corresponding to the same annual exceedance rate for the whole period range yield the site-specific UHS. Then, the differences between response spectrum of synthetic ground motions and UHS are calculated for each period. The squares of differences are then averaged over the whole period range. The ground motions with minimum mean square difference are selected. The most important advantage of proposed approach is the simplicity of acquiring suitable ground motions as there are plenty of synthetic time histories that are simulated to be region-specific. Besides, response spectrum is a better intensity measure for selecting ground motion than magnitude and distance. This approach also leads to small dispersions between ground motion amplitudes and UHS because they are selected from the ground motions which are already applied for constructing UHS. The selected ground motion records will be used for nonlinear structural analysis in future studies.

IASPEI (Seismology, Geophysics)

S06b - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-2133

Importance of scaling relation in slip-strengthening in various earthquake slips

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Scaling relation of “standard” earthquakes can be explained by the hierarchical property and structure in fracture energy during the coseismic weakening process from the mechanical point of view (e.g. Aochi & Ide, GRL, 2004; Ide & Aochi, JGR, 2005). Hardening process prior to this weakening process is mostly ignored for discussing the coseismic process. However, the form of the strengthening process and scaling relation on the parameter can be important for stress accumulation process from our recent study (Aochi & Ide, SSA, 2015). For the simplicity, we suppose a simple equation, $T(w) = T'(w/w_c)^g \exp(1-(w/w_c)^g)$, where shear friction T is a function of cumulative slip w and with a factor g (>0), a constant T' and characteristic length w_c. The numerical simulations suggest that slip deficit rate (delayed slip and consequent weakening process) is size-invariant under a constant loading rate if w_c is proportional to the patch size and g = 1. Furthermore if w_c is scale-dependent and g is sufficiently larger than 1, the slip deficit rate is inversely related to the patch size. The behavior of a superposition of small and large patches becomes more complex. In such case, the peak of the friction may appear differently, namely w can be newly given by $w=w-w_0$, where w_0 is a particular constant for each patch in a seismic cycle. This parameter differentiates the role of small patch during the sliding of the surrounding large patch, particularly when w_0 of small patch is larger than w_c of large patch. When a nested structure of a large and some small patches are externally loaded, the rupture on these patches should occur incoherently. In such case, the rupture of small patch may be considered as fluctuation of rupture front, which radiates high-frequency waves efficiently.

IASPEI (Seismology, Geophysics)

S06b - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-2500

A Study of Ground Motion Modeling in the Sicily channel based on the Empirical-Stochastic Method

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Developing a strong ground motion attenuation relationship with the standard empirical modelling approach presents several challenges. Empirical ground motion attenuation models that have been developed are based broadly on a tectonic regime and regional variations are typically not parameterized. Furthermore, it is particularly important to evaluate them for regions where strong-motion data are lacking and only moderate earthquakes are available. Another approach of attenuation modelling is by means of stochastic simulations using local scaling relationships. The objective of this study is to develop the "path" and "source" model that is representative of the study area that can be used in the simulations. In order to empirically obtain the scaling relationships for the high-frequency ground motion, regressions are carried out on a large data set using background seismicity (about 15955 waveforms from 1968 regional earthquakes with $2.5<M<4.5$) that occurred in the Sicily channel. The obtained "path" components are representative of geometrical and whole path anelastic attenuation. The "site" components are modelled are representative of the crust and the shallow (modeled through the kappa parameter) attenuation effects. We also quantify the "effective duration" of the ground motions as a function of frequency and hypocentral distance. A modeling effort is then undertaken using the random vibration theory stochastic tool in order to produce a predictive relationship of engineering interest. The predictive capabilities of our weak-motion-based model are tested outside and within the magnitude range of the original data set of calibration by comparison to existing observations, as well as against published strong-motion-based equations.

IASPEI (Seismology, Geophysics)

S06b - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-3442

Coupled finite element simulation of earthquakes and tsunami inception: A casestudy of the 2011 Tohoku-Oki earthquake and tsunami

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We address the coupled nature of earthquakes and the resultant tsunamis through a case study of the 2011 Tohoku-Oki event. We achieve this by means of simulations carried out using Hercules, the parallel octree-based finite element earthquake simulator developed by the Quake Group at Carnegie Mellon University (Tu et al., 2006). As a recent improvement to Hercules, we have incorporated acoustic wave propagation in the ocean into our simulations to capture the generation and the offshore propagation of tsunami waves.

Suboceanic earthquakes and the tsunamis triggered by seismic faulting are naturally coupled events. Yet, traditionally they have been studied separately. Some recent studies have addressed the coupled nature of these two events, mostly through weakly-coupled simulations in which the feedback from the ocean waves to the solid domain were ignored. Such feedback can be significant, especially for the slow rupture events of which the 2011 Tohoku-Oki earthquake is a major example. Here, we primarily focus on the generation and offshore propagation of the tsunami waves using a seismic velocity model that is a combination of the two publicly available seismic velocity models of Japan.

IASPEI (Seismology, Geophysics)

S06b - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-3727

Splitting "f-max": Separating attenuation-controlled and source-controlled contributions into the upper cutoff of acceleration spectrum of a local earthquake

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Fourier acceleration spectrum of a local earthquake, corrected for distance-related loss, typically shows a plateau, with an upper cutoff at f $=f_{max}$. Since 1980s, site-related loss (parameterized as $kappa_0$) is assumed to form this cutoff. However, evidence accumulates indicating that the "f_{max}" feature is a complex one, caused by combined effects of site attenuation and source spectral shape. The source-controlled component of f_{max} shows itself in the broad scatter of estimates of $kappa_0$ and Q. Sometimes it can be observed directly. This factor may emulate attenuation, biasing loss estimates. Thus, one needs to separate the named effects. Toward this end, the following processing sequence was performed in iterative manner: (1) use preliminary loss estimates (Q(f) and $kappa_0$) and estimate source acceleration spectrum; (2) identify the frequency range [f_l, f_h] where this spectrum is nearly flat; (3) adjust the estimates of Q(f) and k_0 using only the [f_l, f_h] segment of the observed spectrum. In this way, the estimates of Q(f) and $kappa_0$ are found. Still, the selection of the [f_l, f_h] range may be ambiguous, and a robust procedure is needed. This kind of analysis was applied to several hundreds of S-wave spectra of small to moderate Kamchatka earthquakes with hypocentral distances 50-250 km. In less than half of the cases, the value of f_h is defined by the upper limit of the instrument bandwidth or by low S/N value, with no indication of source origin. In remaining cases, the origin of f_h is ascribed to source spectrum shape, and f_h is understood as the 3rd corner frequency, f_{c3}, of a source. Despite significant scatter, f_{c3} values depend on magnitude ($f_{c3} \sim M_0^{-0.07-0.09}$). Loss estimates are close to $kappa_0$=0.03 s and Q(f)=150 f $^{0.50}$ for the 0-100 km distance range.

IASPEI (Seismology, Geophysics)

S06b - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-4084

Strong Motion Simulation of Subduction Mega-earthquakes using a stochastic generation

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Important accelerograms have been recorded in the last well recorded earthquakes in Chile: Tocopilla 2007 (Mw 7.7), Maule 2010 (Mw 8.8) and Iquique 2014 (Mw 8.1). The records show important differences among the accelerogram components of a same station (2 horizontals and 1 vertical components). The traditional stochastic generation of strong motion considers only vertical incident rays of S waves, simulating one generic horizontal component. We improve this technique to simulate the arrive to free surface of the P, SV and SH waves simultaneously. Then, we generate 3 components strong motion. We considered a stochastic finite-fault method and the propagation of seismic waves include: stratified velocity models, incident and azimuth angles, free surface factors and energy partition. Our simulation reproduce adequately the synthetic strong motion in a wide frequency range (0.1-20 Hz) for the three components records. The comparison of synthetic and real data shows a good correlation, considering time history and frequency evaluations. Finally, we propose several potential rupture scenarios for mega-earthquakes (Mw 9.0) in northern and Central Chile. Then, we generate strong motion data on hard rock. The simulation shows values of peak ground acceleration around ~1 [g] for some sites.

IASPEI (Seismology, Geophysics)

S06b - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

IUGG-4682

Strong ground motions from multi-scale heterogeneous-source model for the mega-thrust subduction earthquakes

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A giant earthquake of Mw 9.0 occurred in the subduction zone off the Pacific coast of Tohoku in Japan on March 11, 2011. This earthquake was observed by dense networks of geophysical instruments including strong-motion, teleseismic, tsunami, and geodetic sensors. Most of slip distribution inverted from long-period records such as geodetic and tsunami data are placed at depths shallower than the hypocenter toward the Japan Trench. The observed strong motions have five wavepackets with an impulsive onset. The short-period source model has been also studied by comparing the observed strong motion records from the mainshock with synthesized motions based on the characterized source model and the empirical Green's function method. Short-period ground motions of engineering interest were found to be generated mainly from five small-asperities on the down-dip edge running roughly north-south in the source area. To generate the impulsive motions at the onsets of the wavepackets, it is necessary to assume that stress parameters inside the SMGAs are not uniform but more heterogeneous. Then, we propose multi-scale heterogeneous-source model as a recipe of predicting strong ground motions for mega-thrust subduction earthquakes.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-305

An investigation of components of ground motion variability using data from Iranian Strong Motion Network

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In ergodic hazard assessments, ground motion prediction equations are derived based on data observed in multiple stations due to different seismic sources. Hence, at single sites, the standard deviation of the GMPE is influenced by the statistics of the spatial variability of ground motion rather than the temporal variability. This usually leads to unrealistically large hazard estimates especially over long return periods. To overcome this problem, the variability at single sites should be explored in order to remove the components which are repeatable rather than aleatory. Based on an extensive dataset of strong ground motions consisting of qualified recordings from shallow crustal earthquakes, a set of GMPEs are developed for Iran. The residuals have been analyzed and the ergodic standard deviation is decomposed into its source (interevent), site (intraevent) and residual components. The epistemic uncertainty of the site term is then estimated. The values of single-station sigmas are obtained for the stations having sufficient number of recordings. The ergodic standard deviations of 0.23-0.35 log10 units are reduced by about 15-30% for the single station sigmas. Upon using in hazard calculations, these single-station standard deviations will lead to reduced and more realistic hazard levels for low probabilities of exceedance.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-306

Variability estimation in ground motion around Istanbul based on the probabilistic dynamic rupture scenarios along the North Anatolian fault

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Variability of ground motion estimation according to various earthquake scenarios is studied in the region of the Sea of Marmara around Istanbul, Turkey, through numerical simulations using a 3D finite-difference method with CPU-GPU implementation. The earthquake scenarios dynamically simulated based on mechanical models are given with probability according to the geological, geophysical and seismological hypotheses. We adopt a 3D geological model of the Sea of Marmara taken into account of the basin structure (down to about 10 km depth) and the existence of the Sea layer (1.5 km depth at max.). Although beneath the land part around the Sea of Marmara is briefly a 1D structure, the influence of the 3D structure of the basin on the ground motion caused by the earthquakes along the North Anatolian fault is significant. Various earthquake scenarios of a magnitude of about 7 lead to a very heterogeneous ground motion pattern. For the selected points, we carry out statistical analysis on its characterization. In Istanbul area, a very strong ground motion (peak ground velocity larger than 1 m/s) may not be the most probable scenario, but has a probability of a few percents in the case where the stress drop is extremely high enough to lead to a super-shear rupture propagation.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-307

Characterizing uncertainties in neo-deterministic seismic hazard maps

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The procedure for the neo-deterministic seismic zoning, NDSHA, is based on the calculation of synthetic seismograms by the modal summation technique. This approach makes use of information about the space distribution of large magnitude earthquakes, which can be defined based on seismic history and seismotectonics, as well as incorporating information from a wide set of geological and geophysical data (e.g. morphostructural features and ongoing deformation processes identified by earth observations). NDSHA defines the hazard from the envelope of the values of ground motion parameters determined considering a wide set of scenario earthquakes; accordingly, the simplest outcome of this method is a map where the maximum value of a given seismic parameter is associated to each site.

In NDSHA the treatment of uncertainties is performed by sensitivity analyses for key modelling parameters, and accounts for the uncertainty in the prediction of fault radiation and in the use of Green's functions for a given medium. The seismic sources used in the simulation are defined from earthquakes catalogue information, seismogenic zones and seismogenic nodes. Because the largest part of the existing catalogues is based on macroseismic intensities, a rough estimate of ground motion error can therefore be the factor of two, intrinsic in MCS scale. In this study we analyse the uncertainty in NDSHA maps due to the catalogue random errors in magnitude and localization. Moreover, for selected areas, we evaluate the ground motion uncertainty due to different input parameters, so as to characterize the resulting error as well as their relative contribution. The definition of confidence intervals associated with NDSHA maps will provide essential information to assess their performances.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-308

Considering intensity measure distributions in the record selection procedure

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Record selection plays crucial role in the nonlinear analysis of structures. Several approaches have been emerged in this area of research in which the Generalized Conditional Intensity Measure (GCIM) is one of them. This approach takes the (log-normal) distribution of different (scalar) Intensity Measure (IM) into consideration. Then the records which have the closest match with these IM distributions are selected. This approach is comprehensively assessed in this paper in order to examine its efficiency. A set of 267 pairs records are selected with the magnitude range greater than 5 and the distance less than 100 km. Seventeen IMs are taken into account and their (log-normal) cumulative distribution functions are calculated. The considered IMS are: Spectral acceleration at T= 0.1, 0.2, 0.3, 0.5, 1.0, 2.0, 5.0, 10.0, Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Arias Intensity(IA), Cumulative Absolute Velocity (CAV), Displacement Spectrum Intensity (DSI), Acceleration Spectrum Intensity (ASI), Spectrum Intensity (SI) and Duration (Ds575, Ds595). Then, eight records are selected among the whole dataset in which their CDFs have the minimum deviations when compared with the CDFs based on the whole dataset. The Genetic Algorithm (GA) is employed in order to solve this optimization problem.

The response of the given structure was calculated by means of the incremental dynamic analysis. The results show that although the selected records have fully compatible CDFs with the CDF based on the whole records, however, the structural response is meaningfully different. This difference is more significant in the 16^{th} and 84^{th} fractiles.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-309

A simplified source model for strong ground motion simulation - Pseudo point-source model

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The pseudo point-source model (Nozu, 2012) is a simplified source model for strong ground motion simulation. Conventional extended source models often consist of rectangular subevents called ‘asperities’ or ‘SMGAs’ on the fault which generate strong ground motions. In these models, the effect of rupture propagation is taken into account by summing up contributions from divided subfaults. In the pseudo point-source model, however, detailed spatiotemporal distribution of slip within a subevent is not modeled. Only the source spectrum of each subevent is modeled and it is assumed to follow the omega-square model. This means that the parameters concerning the size of the subevents and rupture propagation are not involved in the model and the effect of rupture propagation is not explicitly considered. Instead, it is implicitly considered by introducing a corner frequency which is inversely proportional to the size of the subevent. Another important feature of the model is that it is intended to be used with the empirical site amplification and phase characteristics based on the records of smaller earthquakes to make the best use of strong-motion database. The empirical site amplification factors are evaluated by the generalized inversion technique and phase characteristics of past smaller earthquakes are directly used in our simulations.

This model has successfully been applied to past earthquakes including the 2011 Tohoku Earthquake. It is interesting to see such a simple source model can yield good results for large earthquakes once it is combined with the empirical site amplification and phase characteristics. On the other hand, we recognize some errors which could be attributed to the effect of rupture propagation. We will discuss this point in the presentation.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-310

Study of the "damaging" features of a seismic signal trough the development of an adaptive filter based on the S-transform.

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We investigate the time-frequency features of the seismic signal controlling the structural behavior. With this aim, an adaptive filter is developed by applying a Tukey windowing on the pulses identified on the Stockwell transform, a time-frequency representation whose peculiarity is to preserve the phase of the original signal, keeping the causal nature of the seismic input. The technical issues on the filter development are mainly related to the Gabor uncertainty principle, the Stockwell inversion procedure, and the filter settings.

The filter has been applied to 183 strong ground motions with magnitude greater than 6.5, recorded at a hypocentral distance less than 30 km. The two data sets of unfiltered and filtered data are then inputted in a masonry model and the induced structural responses are analyzed. We observe that, if the strongest pluses are not centered on the structure fundamental frequency, even when the signal amplitude is not significantly reduced and the PGA is unchanged the filtered signal is more benign. By centering the filter on the structure fundamental frequency, we are able to isolate small energy pulses which contribute to a little fraction of the total signal energy, but whose effects on the structure are comparable with those induced by the unfiltered signal.

This technique is useful to validate synthetic and real signals used as input for dynamic analysis or shaking tables experiments.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-311

Frequency-dependent directivity effects from small earthquakes in Abruzzo region, Italy

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Directivity-induced amplification effects are well recognized only at low frequency (f < 1 Hz) on strong motion data recorded close to the source of large magnitude events, while no clear evidences are found at higher frequencies and for small-to-moderate-magnitude earthquakes. To date, there is a long standing controversy both from theoretical and observational point of views on to what extent is the strength of directivity effect, and what is its frequency and azimuthal dependence. In this work, we present unambiguous observations of directivity effects for small events (magnitudes 3-4) utilizing 261 aftershocks of the Mw6.3 2009 L'Aquila earthquake (central Italy). For these events, we evaluate apparent source spectra at the recording sites by means of removing path and site effects using standard Generalized Inversion Technique. At selected frequencies, we evaluate the residuals, defined as differences between the apparent source spectra and their mean, and investigate their azimuthal and frequency dependence. Considering only 10 strongly directive events with very good azimuthal coverage, we observe a remarkable decrease of the directivity amplification at high frequencies (in particular at frequencies greater than roughly ~5 times the corner frequency of the respective event). We interpret that this diminution is related to the earthquake source effects, since it is observed at sites located both close and far from the epicenters.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-312

Comparison different intensity measures for SDOF systems due to pulse-likenear-fault ground motions

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Performance-Based Earthquake Engineering (PBEE) involves dynamic analysis of a structure or system subjected to ground motions. Selecting the input ground motions can be effective as much as structural modeling on the results of the analysis. To estimates structural response precisely, it is important to understand and properly account for the ground motion properties that affect these response estimates. Presenting a proper criterion as an "Intensity Measure" (IM) to select ground motions can reduce the errors in the structural analysis remarkably. Experiences from previous earthquakes show that pulse-like near-fault ground motions indicated by a velocity pulse, have caused large responses in the structures, and their effects cannot be well described by traditional intensity measures such as spectral acceleration at the structure's first-mode period, Sa (T1).

In this paper 162 SDOF with fundamental period [0.1-2.0] second and ductility range [2-12] under more than 90 near-field excitations contain directivity pulses were investigated. More than 30 single IMs and around 30 multi-parameters IMs consist of linear combination of dimensionless parameter were used. Genetic algorithm was applied to determine linear combination coefficient factors in multi-parameter IMs such that the best correlation with displacement response of the SDOF systems can be achieved. All IMs were compared to find out which combination has the best correlation. Results show that PGA/PGV ratio has the best correlation with displacement response of the SDOF systems.

IASPEI (Seismology, Geophysics)

S06p - S06a/S06b Strong Ground Motion: Open session, SGM Record Selection and Earthquake Scenarios

S06p-606

Stochastic earthquake source model: the omega-square hypothesis and the directivity effect

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Recently A. Gusev suggested and numerically investigated the doubly stochastic earthquake source model. The model is supposed to demonstrate the following features in the far-field body waves: (1) the omega-square high-frequency (HF) behavior of displacement spectra; (2) lack of the directivity effect in HF radiation.The model involves two stochastic elements: the local stress drop (SD) on a fault and the rupture time function (RT) with a linear dominant component. The goal of the present study is to investigate the Gusev model theoretically and to find conditions for (1) and (2) to be valid and stable relative to receiver site. The models with smooth elements SD, RT are insufficient for these purposes. Therefore SD and RT are treated as realizations of stochastic fields of the fractal type. The local smoothness of such fields is characterized by the fractional (Hurst) exponent H, $0 < H < 1$. We show that the omega-square behavior of the model is achieved approximately if the rupture time function is almost regular (H~1) while the stress drop is rough function of any index H. However, if the rupture front is linear, the local stress drop has to be function of minimal smoothness (H~0). The situation with the directivity effect is more complicated: for different RT models with the same fractal index, the effect may or may not occur. The nature of the phenomenon is purely analytical. The main controlling factor for the directivity is the degree of smoothness of the two dimensional distributions of RT random function.

IASPEI (Seismology, Geophysics)

S06ca - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-1493

How do earthquake stress drop variations reflect in strong motion intensity observations?

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The physical properties of the seismic source play a major role in the generation of earthquake ground motions. One of the key parameters used in this context is the stress drop since it can be directly linked to the high-frequency spectral level of ground motion, and it is an important input parameter for ground motion modeling. Classically determined stress drop estimates from moment-corner frequency analysis have been shown to be extremely variable, and this to a much larger degree than might be expected from the decomposition of ground motion variability into its between-event and within-event components. This discrepancy raises the question of whether classically determined stress drop variability is too large, which would have significant consequences for ground motion prediction for seismic hazard analysis.

We use the wealth of high-quality data available in Japan to investigate this issue. Non-parametric ground motion models have been derived on these data as reference models, and we investigate the relation between the between-event terms for the individual earthquakes with stress drop estimates determined nation-wide for crustal earthquakes. The analysis is carried out for JMA equivalent seismic intensity, PGA and PGV data. Our results indicate a correlation of the between-event terms with stress drop, however with the interesting effect of the appearence of two major families of events with widely different stress drop, yet similar range of between-event terms. This effect is in agreement with the observation made by Cotton et al. (2013), namely that the resulting between-event variability is significantly smaller than the stress drop variability. The potential reasons for these results as well as their implication will be discussed in the presentation.

IASPEI (Seismology, Geophysics)

S06ca - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-2342

NGA-West2 Ground Motion Model for Vertical Response Spectra

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A ground motion model (GMM) was developed for the vertical components of peak ground acceleration (PGA), peak ground velocity (PGV), and 5%-damped elastic pseudo-absolute acceleration response spectral ordinates (PSA) at vertical periods ranging from 0.01 to 10 sec. The extensive PEER NGA-West2 ground motion database for shallow crustal earthquakes in active tectonic domains was used in our GMM development.

A GMM was also developed for the vertical-to-horizontal (V/H) ratio. The V/H model includes the median prediction of the V/H ratio and its aleatory within-event, between event, and total standard deviations. Both vertical and V/H ground motion models incorporate period-dependent magnitude saturation, style-of-faulting effects, hypocentral depth and fault dip effects, geometric attenuation, regionally dependent anelastic attenuation and site response, hanging-wall effects, and magnitude-dependent between-event and within-event aleatory variability. We consider both vertical and V/H ground motion models to be valid for worldwide shallow crustal earthquakes in active tectonic domains for magnitudes ranging from 3.3 to as large as 8.5, depending on the style of faulting, and distances as far as 300 km from the source. This paper presents a summary of our new GMMs.

IASPEI (Seismology, Geophysics)

S06ca - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-2475

A New Framework for Developing Response Spectral Ground-Motion Prediction Equations from Empirical Models of Fourier Spectra and Duration of Ground-Motion

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One of the major challenges associated with the current practice of a probabilistic seismic hazard assessment (PSHA) is to adjust empirical ground motion predication equations (GMPEs) for application in different seismological conditions. This study presents a complete framework for the development of a response spectral GMPE, easily adjustable to different seismological environments; and that does not suffer from the technical problems associated with the adjustment in response spectral domain. Essentially, the approach consists of deriving an empirical FAS (Fourier Amplitude Spectrum) model along with an empirical model for a RVT optimized duration (D_{rvto}). The two empirical models are combined within RVT framework to obtain the full response spectral ordinates. In addition to that, the current approach also involves a stochastic model based extrapolation of Fourier spectral amplitudes beyond the available frequency range of the individual acceleration traces. For that purpose, stochastic model parameters were also determined by inverting the Fourier spectral data using an approach similar to the one as described in Edwards and Faeh, (2013). Although, the main motive of the presented approach is to address the adjustability issues of response spectral GMPEs; comparison, of median predicted response spectra with the other regional GMPEs indicate that presented approach can also be used as a stand-alone model. Besides that, a significantly lower aleatory variability ($\sigma<0.5$ in log units) in comparison to other regional GMPEs, at shorter periods brands it to a potentially viable alternative to the classical regression (on response spectral ordinates) based GMPEs for seismic hazard studies in the near future. RESORCE-2012 dataset was used for the presented analysis.

IASPEI (Seismology, Geophysics)

S06ca - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-4620

Ground motion prediction equation accounting for region specific adjustments

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The quantity and quality of information included in the data sets used to derive a Ground Motion Prediction Equation (GMPE) constrain the complexity of the functional form which, in turn, controls the trade-off between accuracy in predicted median ground motion and overall uncertainty in the model. With increasing model complexity, the compilation of large data sets including strong motion data from several regions becomes unavoidable. RESORCE 2014 (Akkar et al 2013) provides for European and Middle East regions the latest and most comprehensive compilation of homogeneously processed waveforms for GMPE studies. However, the single-country contributions to the composite data set are strongly unbalanced in terms of number of events, site characterization, magnitude and distance ranges. In this study, we exploit the RESORCE-2014 dataset to derive new GMPEs using the Nonlinear Mixed Effects Regression (Stafford 2014) which allows properly accounting for such group specific variations. Preliminary results show statistically significant variations in the anelastic attenuation at high frequencies among Italy, Turkey, and other regions, in agreement with previous studies (e,g, Boore et al. 2014). We apply different grouping schemes on region, site condition, magnitude and distance intervals to discuss the impact of selected random effects on the GMPE coefficients and, on the between-event and between-station variability, as a first step towards site corrected GMPEs.

IASPEI (Seismology, Geophysics)

S06cb - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-2712

Ground motion prediction equations and ensemble models: Comparing the results of italy and Japan

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The Ground Motion Prediction Equations (GMPEs) are likely the largest sources of aleatory variability and epistemic uncertainty in Probabilistic Seismic Hazard Assessment (PSHA). So, the choice of appropriate GMPEs for PSHA is essential. Usually, this problem is tackled through a logic tree even though this methodology has several drawbacks that are not yet solved. Our work is aimed to build, apply and evaluate a procedure that replaces the logic tree applications introducing an objective criterion that may overcome the known drawbacks associated with the logic tree. In particular, we consider a set of pre-selected GMPEs, then we rank them and create a “Model Ensemble” (EGMPE); finally we explore and compare the forecasting performances of each single GMPE with respect to EGMPE, and its impact in hazard analysis. This comparison is made also accounting for possible important factors, such as the tectonic stress regime. Moreover, to better understand limits and effects of our procedure on the forecasting performances for different data (type/quality and seismic activity) and region of applicability, we compare the results obtained for Italy and Japan regions that are very different for quality of data, seismic activity, extension area and a geodynamic point of view.

IASPEI (Seismology, Geophysics)

S06cb - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-3057

Ground motion prediction equations for site-specific PSHA: the case of Northern Italy

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The aim of this work is to investigate the ground motion features of Northern Italy, strongly affected by the presence of a large alluvial basin (Po Plain). As first step, we compiled a qualified strong-motion dataset, DBNI (from ITACA2.1: http://itaca.mi.ingv.it), selecting: i) events in the magnitude range (M_W or M_L) 4.0 - 6.4; ii) records with distance (R_{JB} or R_{epi}) lower than 200 km and iii) focal depths lower than 30 km. Overall, DBNI is composed of 2785 waveforms relative to 329 stations and 112 events occurred in the period 1976 – 2014. The dataset is characterized by two main seismic sequences (1976-Friuli and 2012-Emilia).

The LLH method proposed by Scherbaum et al. (2009) has been used to rank different existing ground motion models calibrated over global, Eurasian or Italian datasets in the period range 0.04-4s.

The residual analysis reveals that existing models cannot entirely capture the features of the observed ground motion in the examined period range. Therefore, the availability of such data set allows us to derive a local GMPEs for the geometrical mean of horizontal components of PGA, PGV and 5% damped SA (T=0.04-4s). Regression on vertical-to-horizontal ratio (V/H) of the same IMs is also performed.

The ground motion variability at single sites has also been investigated (Rodriguez-Marek et al. 2011; Luzi et al. 2014), for site-specific seismic hazard assessment or identifying stations affected by peculiar site effects.

IASPEI (Seismology, Geophysics)

S06cb - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-3782

New worldwide equations for predicting PGA, PGV and 5% damped PSA based on selected data from the SIMBAD database

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Ground Motion Prediction Equations (GMPEs) are essential parameters in seismic hazard analysis. With the introduction of probabilistic approaches for the estimation of seismic response of structures, also known as performance based earthquake engineering framework; new tasks are defined for response spectrum such as the reference criterion for effective structure-specific selection of ground motions before Nonlinear Time History Analysis (NLTHA).

One of the recent efforts to introduce a high quality databank of ground motions and the corresponding selection scheme is the development of SIMBAD database by Smerzini and Paolucci (2013), which is designed to improve the reliability of spectral values at all natural periods by removing noise with modern proposed approaches (Paolucci 2012). In the calculation of target response spectrum for selection methods based on spectral shape, it is preferred to use a consistent GMPE with the general characteristics of the whole databank.

In this paper, a new worldwide GMPE is proposed by using SIMBAD ground motions to minimize the errors related to presence of noise at long periods. To determine regression coefficients, 210 three-component records of 35 earthquakes with magnitude ranging from M_w 5 to M_w 7.1 and epicentral distances lower than 40 km selected from SIMBAD are used. The formulation for the prediction of PGA, PGV and 5% damped spectral acceleration are evaluated. Finally, the proposed model is compared with similar models both qualitatively and quantitatively. It can be concluded that the proposed models are in a relatively good agreement with other available worldwide attenuation relationships, while the prediction ability is improved in case of strong ground motions recorded at close distances to the rupture.

IASPEI (Seismology, Geophysics)

S06cb - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-4230

Ground motion prediction equations and site amplification factors for national seismic hazard mapping: Their 2015 application in Canada

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Ground-motion prediction equations (GMPEs) and their epistemic uncertainty are a key input to seismic hazard assessments, as they specify the expected ground-shaking amplitude as a function of magnitude and distance. Common practice in probabilistic seismic hazard assessment is to weight many published GMPEs in a logic tree of many branches. Instead we applied a “representative suite” (Atkinson et al., SRL 2014) approach to the definition of GMPEs and their epistemic uncertainty for use in seismic hazard mapping in Canada. The approach defines a lower, central, and upper GMPE for each type of earthquake (eastern crustal, western crustal, interface, inslab, offshore) by considering the spread of alternative published GMPEs and data that may be used to constrain the GMPE choices. Our proposed 3-branch model is simple and efficient for national seismic hazard mapping (contrast single-site calculations with the ~250 000 sites needed for the 2015 National Building Code of Canada (NBCC) seismic hazard maps), and gives similar hazard results. NBCC seismic hazard is mapped on the reference Site Class C, with Vs30=450 m/s. To predict shaking on other soil or rock sites, NBCC2015 replaces the Fa and Fv factors used in previous editions (and still in use in U.S. codes) by F(T) factors for each period (0.2 to 10 s) of spectral acceleration plus PGA and PGV. Ground shaking intensity affecting the amplification factors is quantified by PGAref, where PGAref =PGA for western sites, but =0.8*PGA for eastern sites. The latter show higher PGA values than the former for the same short-period spectral shaking, and so the eastern values need to be reduced to avoid applying too-large non-linear reductions to the predictions.

IASPEI (Seismology, Geophysics)

S06cb - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-4470

Refinement of crustal velocity structure model for ground motion simulations in southwest Japan using interstation green's functions

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The crustal velocity structure model is one of important factors to quantitatively predict long-period ground motions from future mega-thrust earthquakes in Japan. We are trying to use interstation Green’s functions estimated by the seismic interferometry technique for validating and improving the crustal velocity structure model in southwest Japan. We have obtained the information on the interstation Green’s functions in the period range 2–10 s from continuous records of 24 F-net broadband stations in southwest Japan (Asano et al., 2011). Then, we have checked the performance of present three-dimensional crustal velocity structure model (Iwata et al., 2008) in this region by comparing the synthetic and observed interstation Green’s functions, and noticed that we need improve the velocity and thickness of the topmost layer to match the travel time and waveform characteristics of the Rayleigh wave in this period range.

In this study, we divided the topmost layer of the original model (Vp 5.0 km/s, Vs 2.7 km/s) into two layers (Vp 5.0 km/s, Vs 2.7 or 2.9 km/s and Vs 5.5 km/s, Vs 3.2 km/s). Then, we calculated the Green’s function by a vertical single force applied to the ground surface for every station-pairs by changing the thickness of these two layers. The Green’s functions are simulated by the finite difference method. By comparing the synthetic and observed Green’s functions, we find appropriate thickness for each station-pair to consider the regional difference of surface layers. Finally we combine these results to refine the three-dimensional crustal velocity structure model in southwest Japan.

IASPEI (Seismology, Geophysics)

S06cb - S06c Strong Ground Motion: Ground Motion Prediction Equations

IUGG-4895

Contribution of the National Accelerometric Network of Ecuador to the selection of GMPEs

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The National Accelerometric Network of Ecuador has recorded several earthquakes since 2009, the year of the first station installed. Some of these tremors have been felt by the community and have caused minor damage in different infrastructure. Although none of them produced major losses, strong ground motion are expected in the future according to both, the historical seismicity and the national seismic hazard map, which predicts values higher than 0.5 g at 475 years return period (PGA) over a significant part of the country (INEN, 2014). This new accelerometric dataset can be used to test recently published ground motion prediction equations (GMPEs) best adapted to the Ecuadorian tectonic context.

In order to contribute to the improvement of the local seismic code, this study aims to propose a group of GMPEs for the probabilistic seismic hazard assessment based on the comparison between the model and strong motion data collected within the period 2009-2014. Two methods are considered for the comparison, simple residuals and log-likelihood (LLH) for crustal earthquakes mainly generated by reverse faults at distances between 2 and 40 km and magnitudes larger than 3.5.

GMPEs are responsible for large uncertainties in Probabilistic Seismic Hazard studies. The GMPEs identified here will be included in the future probabilistic seismic hazard studies in Ecuador.

IASPEI (Seismology, Geophysics)

S06cp - S06c Strong Ground Motion: Ground Motion Prediction Equations

S06cp-586

Ground-motion prediction equations for South Korea peninsula

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Ground-Motion Prediction Equations (GMPEs) play a crucial role for estimating the seismic hazard in any region using either a deterministic or a probabilistic approach. Indeed, they represent a reliable and fast tool to predict strong ground motion given source and propagation parameters. In this work we estimated GMPEs for South Korea peninsula. GMPEs were computed for peak-ground displacement, peak-ground velocity, peak-ground acceleration, and spectral accelerations (damping at 5%) at the at 13 different periods from 0.055s to 5s to obtained a uniform hazard spectra . To this end, we analyzed data from 222 earthquakes recorded at 132 three-component stations of the Korean seismic network. The local magnitude range of the events is $2.0 \leq M \leq 4.9$ and the epicentral distance varies from 1.4 km to about 600 km. A non-linear mixed effects technique is used to infer the GMPEs coefficients. This technique includes both fixed and random effects and allows to account for both inter- and intra-event dependencies in the data. Station/site-specific correction coefficients were also estimated by a statistical approach and were accounted for in the final ground-motion prediction model. We also compared observed and predicted uniform hazard spectra at few metropolitan cities of south Korea and we found good match between observed and predicted uniform hazard spectra.

IASPEI (Seismology, Geophysics)

S06cp - S06c Strong Ground Motion: Ground Motion Prediction Equations

S06cp-587

Ground motion prediction equations of engineering parameters for shallow crustal earthquakes of Iran

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Engineering ground-motion parameters can be used to describe damage potential of an earthquake which depends on the amplitude, frequency content, time duration of the motion, etc. Therefore, for engineering purposes, parameters that capture the effects of these characteristics in their definition are more reliable predictors of the earthquake's damage potential than peak and spectral accelerations. The objective of this study is to propose a set of ground motion prediction equations for peak ground acceleration, peak ground velocity, spectral acceleration, Arias intensity, root-mean-square acceleration, characteristic intensity, Fajfar index, cumulative absolute velocity, and a few other engineering parameters. The strong ground motion data provided by the Iran Strong Motion Network (ISMN) during more than 20 years of strong ground motion recording are employed in a nonlinear least squares regression analyses in order to decipher the dependence of all the preceding parameters on moment magnitude, distance to the surface projection of rupture, local site condition and faulting mechanism. The validity of the proposed equations is assessed using the analysis of residuals by proving that the model is unbiased. The residuals have insignificant averages and are uncorrelated with respect to the predictor variables in the regression and the predicted values. These engineering parameters have been incorporated for the first time in the empirical attenuation relations for Iran. The proposed equations could provide an improved criterion for the selection of earthquake scenarios in terms of engineering ground-motion parameters that are most representative of earthquake damage potential.

IASPEI (Seismology, Geophysics)

S06cp - S06c Strong Ground Motion: Ground Motion Prediction Equations

S06cp-588

Investigating spatial dependence of PGA residuals between measurements and predictions in Austria

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By using data recorded by the Austrian Seismic Network a ground motion attenuation model was developed for Austria (Jia and Lenhardt, 2010). In this presentation, spatial dependence of PGA residuals between the measurements and the predictions based on the derived model were investigated for each station. In addition, influence of weak motion data to the magnitude dependence of our prediction model was studied.

As the first step, spatial dependence of PGA residuals between the measurements and the predictions from our model were investigated. As explained in Jia and Lenhardt (2013), certain differences in the site amplifications were observed between the West- and the East-Austria. For a fair comparison, residuals were normalized before the study for each station. Then the normalized residuals were spatially analyzed and discussed. A good correlation between the majority of residuals and the geological closeness were found.

In total 127 earthquakes with a magnitude between 3 and 5.4 were used to derive our PGA prediction model published in 2011. In this study, the 127 earthquakes were divided into two groups: the first one only includes events with a magnitude smaller than 4, while the second group contains quakes with a magnitude larger than 4. By using the same modeling for estimating PGA attenuation in 2011, coefficients of the model were inverted from the measurements in two groups and compared to the one based on the complete data set. It was found that the group with the weak quakes returned results with very small differences to the one from the 127 events, while the group with strong quakes (ml> 4) gave significantly greater magnitude dependence than the model published in 2011. The distance coefficients stayed nearly unchanged for all three inversions.

IASPEI (Seismology, Geophysics)

S06cp - S06c Strong Ground Motion: Ground Motion Prediction Equations

S06cp-589

Applying of General Regression Neural Network to Ground Motion Prediction Equations of Induced Events in Lubin Copper Basin.

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The Ground Motion Prediction Equation (GMPE) performance using Artificial Neural Network (ANN) was tested. The General Regression Neural Network (GRNN) was chosen as the ANN model due to the speed of learning. The GRNN was tested alone and in cascade with Linear Regression (LR).
Recordings of induced seismicity in Lubin Copper Basin were used for the study. Various combinations of input variables were tested such as energy, epicentral distance, location of the epicenter, position of the station and azimuth. The best results were obtained when location of events was used as input parameter for the GRNN.
The significance of the improvement of the GMPE GRNN model with reference to LR model was verified by the Bootstrap method. It allowed to determine the smoothness parameter of the GRNN with a better generalization capability than in the case of obtaining it by holdout methods.

IASPEI (Seismology, Geophysics)

S06cp - S06c Strong Ground Motion: Ground Motion Prediction Equations

S06cp-590

New worldwide ground motion prediction equations for energy-based intensity measures

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Different Ground motion intensity measures (IMs) are used to characterize features of the earthquake ground motions. There are a variety of scientific evidences confirming the inability of the conventional IMs such as peak ground values and spectral accelerations in the reliable estimation of seismic behavior of engineering structures. Energy-based IMs which are calculated by using time integration of ground motion time-histories can play the role of an effective alternative. For engineering practices, there is an obvious need to develop Ground Motion Prediction Equations (GMPEs) to effectively involve modern IMs in design process.

In this study, two energy-based IMs: Cumulative Absolute Velocity (CAV) and relative input energy (E_{Ir}) are selected. First one represent the destructiveness potential of ground motion in term of total energy content of signal, while the second one is a spectral IM describing the absorbed energy by an elastic single degree of freedom oscillator under ground motion excitation. Worldwide GMPEs are proposed by using selected ground motions from SIMBAD databank.

In order to determine regression coefficients, 210 three-component records of 35 earthquakes with magnitude ranging from M_w 5 to M_w 7.1 and epicentral distances lower than 40 km selected from SIMBAD are used. The formulations for the prediction of CAV and 5% damped spectral E_{Ir} are evaluated. Finally, the proposed model is compared with available similar models both qualitatively and quantitatively. It can be concluded that the proposed models show acceptable agreement with databank in term of different statistical measures of goodness-of-fit. The prediction ability is improved in case of strong ground motions recorded at close distances to the rupture.

IASPEI (Seismology, Geophysics)

S06cp - S06c Strong Ground Motion: Ground Motion Prediction Equations

S06cp-591

MARS: A new tool for macroseismic data regression and analysis

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This work is focused on the development of a tool (named MARS - MAcroseismic data Regression and analysiS) for an integrated analysis of macroseismic intensity datasets in order to support the calibration of Intensity Prediction Equations (IPEs). Modules are developed for: i) data plot; ii) statistical analysis of the dataset; iii) IPEs calibration; iv) analysis of residuals. MARS is designed to develop an in-depth study of large datasets composed by earthquakes and intensity points, as well as by a single event.

Statistical analysis and data plot modules allow users to examine: frequencies of data features (e.g. classes of distances and intensities), intensity distribution on map as well as on graph (intensity versus hypocentral distance).

Regarding IPEs calibration, a module has been dedicated to implement a variety of functional forms. Starting from a basic form (e.g. $I=a+b*M+c*R_{hypo}+d*\log_{10}(R_{hypo})$), it is possible to use more complex magnitude scaling terms, commonly employed in GMPEs. For the IPEs calibration a standard regression approach thought best least squares fit analysis has been implemented.

Another important application regards the analysis of the residuals, in order to evaluate the goodness-of-fit between a given dataset and an IPE through: i) total residuals ($I_{Predicted} - I_{Observed}$) decomposition and analysis; ii) IPEs ranking; iii) calculation of the mean error per event (between-event). Such functionalities help the user to check earthquake parameters and macroseismic intensity attribution, in order ensure the quality of the dataset used for the IPE calibration.

IASPEI (Seismology, Geophysics)

S06cp - S06c Strong Ground Motion: Ground Motion Prediction Equations

S06cp-592

The long-period surface motion of the Mw9.0 Tohoku-Oki earthquake based on GPS and strong-motion sensors

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The GPS displacement time series are today mostly used for the estimation of the transient (period <2sec) and coseismic (static) displacement of an earthquake, while the estimation of the velocity and acceleration is based only on strong-motion sensors and broadband sensors. In this study, we examine whether the GPS records can be used to capture apart from the displacement also the velocity and acceleration of the oscillatory ground motion. For this purpose, we use the 1-Hz GPS network records of the Tohoku-Oki 2011 earthquake processed in Precise Point Positioning (PPP). The derived GPS waveforms were analysed resulting into displacement, velocity and acceleration for periods ranging from 3 to 100s. We find that the ground motions of the sedimentary basins of Japan were large, corresponding to velocity and acceleration larger than 0.15m/s and 0.15m/s^2 , respectively, even for periods greater than 3s. We compare the GPS observables with a Ground Motion Prediction Equation (GMPE) designed for Japan seismicity and find that the Spectral Acceleration (SA) is well estimated for periods larger than 3s and distances ranging from 100 to 500km. Finally, through the analysis of the displacement attenuation plots for the examined period band, we show that the 2011 Tohoku-Oki event is likely composed of multiple rupture patches as suggested before by time-reversal inversions of seismic data.

IASPEI (Seismology, Geophysics)

S06da - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-1259

Relationship between Ko and Vs30 from Taiwan TSMIP data

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High frequency attenuation parameter kappa (k) was analyzed by spectral fitting method (Anderson and Hough, 1984) from the TSMIP (Taiwan Strong Motion Instrumentation Program) strong motion observation data. From the S-wave spectrum of each event recorded by the same station, the spectral attenuation parameter kappa can be calculated from the amplitude decay with respect to frequency. Then based on the each event's hypocentral distance (R) and kappa, we can generate the relationship between k and R. k_0 (k at R=0) can be referred as one of the site factors. In this study, 14133 earthquake records from 1993 to 2012 with 10~150 km hypocentral distance and focal depth smaller than 30 km that recorded by 369 TSMIP strong motion stations are analyzed to calculate the kappa for each station. Due to 263 TSMIP stations selected in this study had Vs30 information from logging measurement (Kuo et al., 2012), the relationship between k_0 and Vs30 can be obtained. In average, k_0 for site classes B is 0.044, C is 0.056, D is 0.066, and E is 0.076 respectively. The k_0 for site class A is 0.034 but it only from the earthquake records of one station due to only one TSMIP station was classified as category A recently.

IASPEI (Seismology, Geophysics)

S06da - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-1953

Influence on source, path, and site effects for amplitude ratios of S-waves to P-waves

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Earthquake early warnings have been issued for the area in which strong shakings will occur, using seismic data triggered by the observation network. Generally, the magnitude and the epicenter of earthquakes were estimated using the initial P-wave observed at the nearest seismic station from the epicenter. However, in the case of earthquakes which induce strong ground motions in the near field, a method to directly predict amplitudes of S-waves using those of P-waves could be able to issue earthquake early warnings more simply and surely than the present method. Therefore, we evaluated amplitude ratios representing the influence of source and path effects (a_1) and those representing site effects (a_2) using seismic records observed on the surface and those in the seismic bedrock for each seismic station of KiK-net in the Kanto Basin, Japan. a_1 and a_2, which were amplitude ratios of S-waves to P-waves observed in the seismic bedrock and amplitude ratios of S-waves observed on the surface to S-waves in the seismic bedrock, respectively, were evaluated for Fourier spectra, peak accelerations, and peak velocities. Amplitude ratios a_2 were larger than a_1; therefore, site effects more largely affected amplitude ratios of S-waves to P-waves than source and path effects. On the other hand, standard deviations of a_1 were larger than those of a_2; therefore, the variability of source and path effects by individual earthquakes more largely affected the variability of amplitude ratios of S-waves to P-waves than the variability of site effects.

IASPEI (Seismology, Geophysics)

S06da - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-1965

Geophysical investigations on landslide area in Buyukcekmece, Istanbul

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In the western part of Istanbul metropolitan area where is heavily urbanized, there are many landslides of various sizes. Under the EU-FP7 project titled with MARsite (Work Package 6), it has been performed a number of near surface geophysical measurements on a pilot landslide. The study aims to discuss the achievement of the integrated geophysical methods in revealing physical and geometrical characteristics of sliding mass. The Buyukcekmece landslide involves upper Oligocene to lower Miocene deposits consisting of silty clays, tuffs and sands. The width and length of the landslide are about 1.5 km and 2 km, respectively. The measurements on the landslide consist of 27 profiles of P-wave refraction, MASW and REMI, 4 profiles of resistivity, and 32 points of ambient noise. It is observed that the soil in the landslide area is highly rugged and disturbed, so caused many problems in the geophysical measurements, for example, affecting the geophone-soil coupling, attenuating the seismic waves rapidly, generating scattered waves, and changing the values in short distance. The penetration depth is the lowest in the refraction method, being 10-20 m, so this method failed for detecting deep-sliding surfaces. The MASW and REMI methods provided information up to a depth of 30 m and 80 m, respectively, but a clear sliding surface could not be detected, depending on both resolution of the methods applied and the lithological character of landslide. The H/V method provides a resonance frequency, but it changes in short distances depending on the complex structure of the landslide.

IASPEI (Seismology, Geophysics)

S06da - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-3163

Microtremor array measurements in Western Taiwan

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We have conducted array measurements of microtremor at more than forty sites in Western Taiwan during the past years. The radii of those arrays are from about 30 to 60 meters according to the space of different sites. The Maximum Likelihood Frequency-Wavenumber Method was adopted in this study to obtain phase velocities of Rayleigh waves as a function of frequency and then a Genetic Algorithm technique based on fundamental mode of Rayleigh waves was implemented to calculate an optimum S-wave velocity model at each site. However, this method sometimes generated dummy layers. We further used a conventional surface wave inversion method and the result of the Genetic Algorithm was introduced as an initial model. Dummy layers were removed during this procedure and the finial model was derived at sites. Logging velocity profiles are also available at some of those sites although most of those logging profiles are with a depth of less than 40 meters. The shallow part of S-wave velocity profiles estimated using microtremor arrays mostly fit very well with the logging profiles. We therefore delineated depth distribution of the engineering bedrock (Vs = 600 m/s) for the Western Taiwan. The depth of engineering bedrock increases from the east (mountain) to the west (coast line) in the study region. The depth contour extends almost along the topographic demarcation between mountain and plain areas in the eastern part. The final S-wave velocity model constructed in this study is the first model of shallow unconsolidated deposits comprising engineering bedrocks for western Taiwan.

IASPEI (Seismology, Geophysics)

S06da - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-3177

Local seismic hazard assessment in alpine environments

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Site characterization of newly installed seismic stations of the Swiss seismic networks has been systematically performed since 2007. In particular, between 2009 and 2015, more than 40 permanent strong-motion stations have been deployed mainly at risk-oriented sites in Switzerland. The procedure includes ambient vibration array measurements, MASW and active seismics, CPT measurements and the analysis of geotechnical lab tests, as well as the collection of information related to geology, the geometry of the underground structure (layering, basin effects, etc) and surface topography.

Passive seismic surveying methods have been developed to include tools that allow the combined analysis of multiple components of ground-motion from ambient vibration array recordings. New methodologies have been developed to retrieve Rayleigh-wave ellipticity, including the sense of rotation; combining active seismic acquisition with passive methods to optimize the use of available instruments; and the identification of 2D resonances in Alpine valleys and in instable rock slopes. Shear-wave velocity profiles resulting from analyses at the stations of the Swiss and Japanese Networks have been used to develop new tools for seismic hazard assessment. The tools facilitate the prediction of site-specific anelastic amplification (including the kappa parameter) from the Vs profiles.

Observed amplification at seismic installations is automatically assessed after each event. Amplification is utilized for validation of the models developed within the site characterization phase, and to categorize the sites according to the presence of 2D or 3D resonances and edge-generated surface waves.

IASPEI (Seismology, Geophysics)

S06da - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-3839

Developing reliable shear wave velocity profiles for site response: Effects of layering parameterization on surface wave inversion

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The inverse problem involved in obtaining a realistic layered earth model from surface wave dispersion data is inherently nonlinear, ill-posed, and mix-determined, without a unique solution. Even if experimental dispersion data could be measured without error, the inversion of such data to obtain representative shear wave velocity (Vs) profiles is prone to serious errors if the model space is poorly parameterized. In cases where a-priori information is not available, one must typically guess how many layers are needed in order to facilitate a realistic inversion. This study utilizes a simple, normally dispersive layered earth model to demonstrate errors that can arise during inversion of even the most basic subsurface stratigraphy if layering parameterization is poorly chosen. The dispersion data for the layered earth model were computed theoretically and assigned realistic uncertainties in order to represent a set of experimental dispersion curves of varying bandwidths typical of field data. These band-limited dispersion curves were then inverted with a global search algorithm utilizing a variety of layering parameterizations. The Vs profiles obtained from inversion were then systematically compared with the actual Vs profile of the model. Results indicate that different types of errors arise depending on whether too few or too many layers are specified during the inversion. These errors are not necessarily evident from the misfit values used to quantify the goodness of fit between the theoretical and experimental dispersion curves. A systematic methodology for determining optimum model parameterizations that will lead to reliable Vs profile recovery is presented.

IASPEI (Seismology, Geophysics)

S06db - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-1846

Spectral element modeling of seismic wave propagation in 1D-1C and 1D-3C linear and nonlinear media including pore pressure effects

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Numerical modeling of seismic wave propagation has been a major topic on ground motion studies using a number of different numerical integration schemes. The consideration of the soil nonlinearity in the modeled media holds an important place in order to achieve simulations consistent with real observations for strong seismic shaking. Additionally, in the presence of strong ground motion in saturated soils, the pore pressure becomes an important parameter to take into account for the related phenomena such as flow liquefaction and cyclic mobility. In this study, first, one component (1C) - seismic wave propagation is modeled in linear and nonlinear media in 1D. Viscoelastic and nonlinear soil rheologies are implemented by use of the memory variables technique and Iwan's elastoplastic model, respectively. Then, the same study is extended to a 1D-3C model and the influence of the pore pressure is included. The developed numerical model is based on the spectral element method with an explicit numerical integration scheme. The ground motion modification due to the presence of different soil layers overlying a relatively rigid half-space is studied by means of several simulations with the 1D-1C and the 1D-3C spectral element codes for different assumptions of the soil rheology in the media and different input motions. A comparison between the results of the 1D-1C and 1D-3C codes and viscoelastic and nonlinear behaviors is made. A final comparison is also made for realistic cases of past earthquakes such as the 1993 Kushiro-Oki and the 1987 Superstition Hills events. Such a study allows to help identifying and understanding dominant phenomena occurring in superficial layers, depending on local conditions and input motions. This is of great help for site-specific studies.

IASPEI (Seismology, Geophysics)

S06db - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-2419

'Atypical' soil behavior during the 2011 Tohoku earthquake (?w = 9)

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Models of soil behavior (vertical distributions of nonlinear stress-strain relations in the upper 100-500 m) during the 2011 Tohoku earthquake ($?_w$=9.0) are constructed for 55 KiK-net sites located in the near-fault zones and recorded the highest peak ground accelerations, including PGA > 1g. The method of data processing was used developed by Pavlenko and Irikura (2003) and previously applied for studying soil behavior at vertical array sites during the 1995 Kobe ($?_w$=6.8) and 2000 Tottori ($?_w$=6.7) earthquakes. During the Tohoku earthquake, "atypical" soil behavior was observed. Instead of widespread nonlinearity of soft soil behavior in near-fault zones and reduction (at the beginning of strong motion) and recovery (at the end of strong motion) of shear moduli in soil layers, as usually observed during strong earthquakes, during the Tohoku earthquake, soil behavior was more linear than we could expect for such a strong earthquake. Shear moduli in soil layers increased with the beginning of strong motion and reached their maxima at the moments of the highest intensity of motion indicating soil hardening. Then, they decreased with decreasing the intensity of strong motion. An increased (compared to weak motion) amplification of seismic waves in soil layers was observed during the main shock, related to the soil hardening at the moments of the highest intensity of strong motion. These site effects evidently contributed to the occurrence of abnormally high peak ground accelerations, recorded by many K-NET and KiK-net stations during the Tohoku earthquake.

IASPEI (Seismology, Geophysics)

S06db - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-4110

Comparative analysis of the seismic wavefield composition on two nearby rock and soil sites in the Argostoli area, Greece

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Two temporary dense arrays have been installed at distinct periods in two close sites located 2 km from one another, one on outcropping rock and the other on recent quaternary deposits, in the Argostoli area (Cephalonia Island, Greece). Both arrays consist of 21 broad band sensors located on 4 concentric circles with maximum diameter 160 m on soft soils, and 360 m on rock. The first array was operated over a 6 month period from September 2011 to April 2012, and the second over a 6 week period in February – March 2014, during the intense aftershock activity following the Cephalonia 2014 seismic sequence. Both arrays recorded several hundreds earthquakes. For each array, a subset of several tens of events with high-quality array recordings was selected, and analyzed with the advanced MUSIQUE three-component processing technique to extract the phase velocity, back-azimuth of the dominant waves crossing the array as well as their identification as Love or prograde/retrograde Rayleigh waves. For the soft site, the wavefield is controlled by the valley geometry, and dominated by locally scattered surface waves carrying up to 80% of the total energy, with predominant back-azimuths coming mainly from the closest valley-edge to the south-west of the site, whatever the location, distance and magnitude of the event. This peculiar wavefield composition will be compared with the one identified with a similar analysis on the rock site array (under processing), in order to identify to which extent the rock site wavefield is controlled by direct waves coming from the source, or by other scattering sources, and whether this wavefield is stable form one event to the other or not.

IASPEI (Seismology, Geophysics)

S06db - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-4858

The Relation between the Directional Dependent Horizontal-to-Vertical Spectral Ratios of Microtremors and the Lateral Heterogeneity at the Basin Edge

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The authors have shown by using a numerical method such as a 3-D spectral element method and calculating the Green's functions of the response at the same point of harmonic loading on the surface from 3-D wave propagation analysis using a 2-D basin structure, it is possible to qualitatively simulate the significant directional dependency that can be seen in H/V spectral ratios of microtremors (HVRM) observed at sites on Uji campus, Kyoto University. When we handle the observed HVRMs separately for the two horizontal components, the NS/UD has higher peak amplitude and EW/UD has higher peak frequency. Also, it has been shown that the shape of the HVRMs are distorted at sites very close to the basin edge (Matsushima et al., 2014). This is an indication that if we observe microtremors at several sites close to the assumed basin edge, it may be possible to identify the conditions of the lateral heterogeneity close to the basin edge in detail.

In this study, we focus on the effect of the basin edge to the HVRMs and study the relation between the basin edge shape and the difference between NS/UD and EW/UD by observing microtremors for two line arrays perpendicular to the 2-D basin in Uji and one line array parallel to the basin edge. As a result, we found that the observed HVRMs show the same characteristics assumed from the HVRMs derived from numerical analysis.

From these results, we can see that the condition of the lateral heterogeneity close to the basin edge changes the characteristics of the HVRMs. If we accumulate the relation between the conditions of the basin edge to the shape of the HVRMs in two orthogonal horizontal directions, we will be able to use the information from the observed HVRMs to determine the basin edge shape.

IASPEI (Seismology, Geophysics)

S06db - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-5202

Local seismic response of sites with pronounced topography: insights from modelling

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Many cases of pronounced amplification evident in strong ground motion recordings have been reported at sites with specific topographic features in last four decades. Although attempts have been made to explain such observations with the effect of the terrain geometry, the strong levels of observed amplification remain unexplained most of the time. In our recent study, we investigated an observed seismic response of several elevated sites in Switzerland and Japan. On one hand, we have not identified any general link between the geometrical features of the surface topography and the observed site response. On the other hand, the subsurface structure presented seismic velocity gradients even at outcropping rock sites. The studied rock sites (Vs30 > 800 m/s), on average, did not exhibit any systematic amplification, while the rest of the sites (Vs30 < 800 m/s) presented frequency dependent amplifications with respect to reference rock condition. The observed amplifications were found linked with strong directionality of ground motions at fundamental frequencies. We have concluded that the observed site response is controlled in first place by the subsurface velocity structure.
In the present study, we make an attempt to explain these observed amplification patterns by means of numerical modelling. In particular, a detailed 3D numerical modelling of seismic response has been performed for a number sites. The simulations are based on 3D finite difference scheme with a curvilinear grid. The joint effects of the terrain geometry and available velocity gradients are investigated. The synthetic amplification functions are compared with the empirical ones, and limits of the adopted models are discussed. The observed and synthetic directionality patterns are compared as well.

IASPEI (Seismology, Geophysics)

S06dc - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-1204

On adequacy of plane-wave approximation for evaluating near-field seismic rotational ground motions: case of P-SV source

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A common approach for obtaining the rotational components of seismic ground motions from the single-station recordings of translational components involves use of the simple relationship between the Fourier rotational and translational amplitudes resulting from the incidence of plane harmonic waves at the free surface. While this approach may work suitably in intermediate or far-field regions, its accuracy in near-field regions is questionable, since the propagating wave fronts are not planar. This is tested in the paper by considering a two-dimensional, P-SV (shear) dislocation source buried in a homogenous elastic half-space. First, the translational motion is obtained in time-domain by analytically solving the kinematic dislocation problem. The rotational motion is then synthesized (from the computed translational motion) by assuming that the translational motion results from the P- and SV- waves incident at the free surface at an angle made by the line joining the source and receiver with the vertical. The amplitudes of the synthesized motion are then compared with those obtained from the exact solution of the kinematic dislocation problem.

The results from numerical simulations for a few source functions indicate that the plane-wave approximation works well in the intermediate and far-field regions. Its adequacy in the near-field regions is, however, sensitive to the source function parameters, source geometry, source depth and seismic wave velocities of the medium. In particular, for the vertically oriented dislocations, if the source rise-time is more than the time taken by the seismic waves to reach the epicenter, the plane-wave approximation is found to underestimate the rotational motion amplitudes by more than one order of magnitude.

IASPEI (Seismology, Geophysics)

S06dc - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-1811

Reducing non-uniqueness in inversion for seismic moment tensors using rotational ground motions

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Especially, on a regional scale the inversion for seismic point-source moment tensors still faces several difficulties. These difficulties include e.g. a sparse and unfavorable data coverage, the necessity of a detailed structural model, and low signal-to-noise ratios, especially for smaller earthquakes ($M<4.5$). Thus, the resolvability of the moment tensor from inversion is reduced. Often, intense constrains are necessary to obtain a reliable solution and the full power of the moment tensor method is not exploited.

The emerging field of rotational seismology comprises the potential to promote almost all fields of seismology. Here, we investigate the potential of rotational ground motion recordings to reduce non-uniqueness in seismic moment tensor inversions, with emphasis on the required measurement accuracy of currently developed rotation sensors. The analysis is based on a synthetic Bayesian inversion that avoids linearizations and provides a comprehensive quantification of uncertainties and trade-offs.

With our results we present how the non-uniquenesses in inversion for moment tensors will be reduced due to the usage of rotational data and how much the information gain is increased. We will show whether it is possible to resolve the full moment tensor without constrains and under which conditions this is the case when including rotational data into inversion.

IASPEI (Seismology, Geophysics)

S06dc - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-2012

More Love waves than Rayleigh waves in the secondary microseism : Study by co-located Ring Laser and STS-2

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The two co-located instruments, a Ring Laser and an STS-2 type seismograph, at Wettzell (WET), Germany, provide a unique opportunity to separate Love waves and Rayleigh waves in seismic noise. We estimated this ratio in the secondary microseism (0.13-0.35 Hz) and found more Love-wave kinetic energy than Rayleigh-wave energy.

We used the Ring Laser to estimate the amount of Love waves and the vertical component of STS-2 seismograph to measure the amount of Rayleigh waves. The first step in our analysis was to obtain stacked Fourier spectra that were least affected by earthquakes. We did this by selecting small-amplitude time intervals first from spectral amplitudes and removing days of earthquakes (M>5.5) by using the GCMT (Global Centroid Moment Tensor) catalogue.

We converted vertical spectra to acceleration spectra and the Ring Laser spectra to transverse acceleration. The latter was achieved by multiplying phase velocity of fundamental-mode Love waves to raw spectral data (e.g., Pancha et al., 2000; Igel et al., 2005; Hadziioannou et al., 2012). For Love-wave phase velocity we used a model by Fichtner et al. (2013).

Comparison shows surface amplitudes are comparable between Love waves and Rayleigh waves. Near the spectral peak (~0.20 Hz), Rayleigh waves are about 20 percent larger but outside this peak region, Love waves have slightly larger than Rayleigh waves.

We also converted these surface acceleration amplitudes to the kinetic energy. The ratio of Love-wave kinetic energy to Raleigh-wave energy shows that Love waves are typically higher in the frequency range 0.13-0.35 Hz, varying 20-40 percent.

The results are generally consistent with Nishida et al. (2008) for Japanese data and require us to think how so much Love waves can exist in the secondary microseism.

IASPEI (Seismology, Geophysics)

S06dc - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-2242

Seafloor ground rotation observations

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We report observations from an experiment we carried out in the North Sea, close to the island of Helgoland in the summer of 2014. A commercial fibre-optic gyro (usually used for navigation purposes) recording ground rotation rate with a sensitivity of approx. 10^{-7} rad/s was mounted on an OBS system together with a broadband seismometer. The system was lowered to the seafloor for about a week. To investigate a potential connection between rotational ground motions around the two horizontal axes (i.e., tilting) we calculate the coherence between the corresponding motion components (e.g., rotations around x-axis and translational motions along y-axis, and vice versa). We find very high correlations, on average exceeding 0.73 in the period interval 7-13 seconds. Correlations seem to increase with noise amplitude. Rotation rate amplitudes are in the range of 10^{-6}-10^{-5} rad/s. This clearly indicates that the horizontal translational components are severely contaminated by rotations around the horizontal axes. We investigate the origin of these rotational motions and correlate with wave height, wind information, and other parameters. In principle, the ground rotation observations allow correcting for the cross-coupling effect thereby improving the S/N on the horizontal translational components. We quantify the improvement of this procedure and discuss general requirements for broadband rotation sensors for OBS applications.

IASPEI (Seismology, Geophysics)

S06dc - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-3485

Effects of rotational motion on near-fault strong-motion data

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Rotational motion related effects include the centrifugal acceleration, effects of gravity and effects of rotation frame. The time histories of these effects are asymmetric in general and taking integration of these acceleration waveforms might have non-zero permanent velocities and displacements. These effects might cause abnormal waveforms which appear as asymmetric acceleration waveforms, a high ratio of the peak values between the vertical and the horizontal components, and baseline drift in the integrated velocity and displacement waveforms. These induced effects are always accompany with the translational motions and have a higher increasing rate than that of translational motions. Therefore, the importance of these effects grow up with the ground motions. There are more and more evidences from rotation-translation (six-component) data and strong-motion records of recent major earthquakes to show that the abnormal waveforms found in the near-fault data are mainly due to rotation induced effects. In a numerical simulation based on empirical scaling relationships indicates that the abnormal waveforms found in a near-fault record in 2008 Iwate-Miyagi earthquake can be reproduced by introducing rotational motions. Fortunately, all these rotation-related abnormal waveforms are correctable if six-component recording are provided

IASPEI (Seismology, Geophysics)

S06dc - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

IUGG-4206

Determination of real backazimuths of local and regional Icelandic earthquakes using single-point six-degree-of-freedom measurements

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We have developed the seismic sensor Rotaphone capable of measuring three translational and three rotational components of both strong and weak ground motions. We have deployed it in the Katla region, South Iceland, for a three-years measuring campaign. During the first eighteen months we have registered hundreds of shallow earthquakes related to active volcanism at local and regional (up to 200 km) distances. Thanks to low noise and mostly a relatively simple geological structure, the recorded data are suitable for research aimed at the possibility to determine the real backazimuth using rotational data. Different methods appropriate for various epicentral distances are tested. As an example of regional events we study records from an ongoing volcanic activity connected with the Bardarbunga volcano, 160 km away from the Rotaphone. Regional epicentral distances allow us to determine the real backazimuth by matching the vertical-axis rotation rate and transverse acceleration and/or by matching the transverse-axis rotation rate and vertical acceleration. These well-known relations, derived under the assumption of a plane wave, are not applicable to closer earthquakes (e.g. the events from South Iceland, 70 km away, or the local Katla volcanic events, about 20 km away, etc.). We have derived more adequate relations under the assumption of a spherical wave. We show that rotation-rate components from local earthquakes cannot be matched to relevant acceleration components only, but that velocity components are also significant. The backazimuth determined using rotational components is studied independently for different phases in the seismogram and it is compared to the backazimuth derived from particle motions and to the geometrical backazimuth.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-524

Vulnerability index estimation using microtremor for Nile delta, Egypt

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ABSTRACT

Understanding how sedimentary basins respond to seismic-wave energy generated by earthquake events is a signi?cant concern for seismic-hazard estimation and risk analysis. The main goal of this study is assessing the vulnerability index, Kg, as an indicator for liquefaction potential sites in the Nile delta basin based on the microtremor measurements. Horizontal Vertical spectral ratio analyses (HVSR) of ambient noise data, which conducted in 2006 at sites representing different sedimentary facies, different embayment thicknesses, and varying liquefaction susceptibility, show good correlations with the sediment thickness and subsurface stratigraphic boundaries. The Kg value is widely ranged from 2.5 to 53. The results of this study show that the weak zones which identified by the high Kg values are located in the southern part of the Nile Delta where the shallow depth of the aquifer and the smallest thickness of the cap rocks.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-525

Prediction of peak ground acceleration with respect to site condition using artificial neural network- A case study for Iran

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The peak ground acceleration (PGA) is an important input parameter for design basis earthquake ground motion and is commonly used to define the ground motions. Therefore, the knowledge about the characteristics of ground motion in a specified region due to relation with PGA can be a very essential factor for civil engineering structures.

The Iran plateau has been crossed by several major fault zones which as a result is one of the most seismically active countries in the world that frequently suffers destructive earthquakes.

In this paper the feed forward back propagation artificial neural networks (FFBPANN), generalized regression neural network (GRNN) and traditional linear regression analyses were used to predict the earthquake PGA. The magnitude, focal depth and three site conditions consisting of rock, stiff soil and soft soil of 40 three component records of 8 events in available stations regarding to their direction (N-S, E-W, Z) in west of Iran were the inputs which coded in MATLAB. In this paper the rock, stiff soil and soft soil site conditions were considered and employed in the code. Comparing the obtained results of employed methods with those really recorded showed that the FFBPANN was superior to GRNN. Moreover, application of linear regression analysis between the measured PGA from the records and those obtained by FFBPANN, showed a modification which increased the prediction performance.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-526

Surface wave inversion using swarm intelligence methods and their application to microtremor measurements

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Surface waves have been increasingly used as an attractive tool for obtaining near-surface shear-wave velocity profiles. Surface wave dispersion curve inversion is a challenging problem for linear inversion procedures due to its highly non-linear nature and to the large numbers of local minima and maxima of the objective function (multi-modality). In order to improve the reliability of the inversion results, we implemented and tested deferent inversion schemes based on Intelligence Swarm and traditional Genetic Algorithm. To evaluate calculation efficiency and stability of Intelligence Swarm to inversion of surface wave data, we first inverted dispersion curves of a two-layer, three different three-layer and four different five-layer synthetic data sets. In this work we focus on the joint inversion of shear-wave velocity, compressional-wave velocity and layer thickness while fixing density according to variable Poisson's ratios. The algorithm we developed here aims at performing nonlinear inversion of fundamental-mode and/or higher-mode Surface-waves. Then, we made a comparative analysis with GA and other Intelligence Swarm methods.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-527

High Velocity Gradients in Shallow Sediment and its Effects on Strong Ground Motion Propagation

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Seismic data collected during explosion experiment on the western coastal plain in Taiwan showed a significant feature of high-energy later arrivals. These high-amplitude multiples almost completely mask the lower-amplitude signals from the deep crust. The later arrivals are identified as free-surface reflected multiples. The nature and generation of these high-energy, multiple diving waves are demonstrated using synthetic examples. Their generation requires the presence of a high-velocity gradient in the shallow crust. A detailed analysis of the observation data provided information on the velocity gradients in this region. An accurate layer-velocity model was constructed based on a one-dimensional waveform simulation and two-dimensional seismic ray tracing modeling for travel times. Actually, the multiple diving waves are excited not only by surface explosions but also by shallow earthquakes. The reflected multiples have been observed from shallow events in this region and recorded by a strong motion array. It is found that shear wave multiples are significant from earthquakes. Numerical simulations for velocity gradient indicated that the repeat arrivals from the multiple diving waves act to extend the duration of ground motions and enhance the amplitude. The high velocity gradient of the sediment layer showed effectively bend any high-frequency seismic incident waves to the free surface, thereby complicating interpretations of seismic signals. Further studies of the propagation of multiple diving shear waves, and of the velocity profile at shallow depths, would improve the accuracy of regional hypocenter determinations, predict the strong ground motions from large earthquakes, and contribute significantly to the site effects and the mitigation of seismic hazards.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-528

Effects of shallow subsurface structures to long-period ground motions, during the 2011 off the Pacific coast of Tohoku earthquake, Japan

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During the 2011 off the Pacific coast of Tohoku earthquake, Japan, large ground motions were observed in the Kanto Region which is located 150 km far from the earthquake source fault. As for this earthquake, the seismic data of more than 1000 were recorded in the Kanto Region by the seismic networks of more than 20 institutes. Complex distributions of earthquake ground motions, due to the heterogeneities of subsurface structures in the Kanto Region, were observed both in high frequencies and in long periods. Especially in the western coast of Tokyo Bay and the Ashigara Valley, large velocity responses of larger than 100 cm/s were observed for a period of 2 to 3 seconds.

At first, to understand the characteristics of long-period ground motions observed in the western coast of Tokyo Bay and the Ashigara Valley, we applied the time-frequency analysis to those seismic data. The long-period ground motions for a period of 2 to 3 seconds are significantly dominated in the main phases for a time window of about 40 seconds, which are mainly composed of body waves. Secondary, to understand the subsurface structures, we carried out array microtremor observations in the western coast of Tokyo Bay and the Ashigara Valley. As a result, thick soft-soil deposits with S-wave velocity of less than 400 m/s were estimated in the both sites. To explain those long-period ground motions for a period of 2 to 3 seconds, we need to understand the shallow subsurface structures including layers of less than Vs 400 m/s at least. Above all, in the Ashigara Valley, the impedance ratio between the soft-soil deposits and the basement plays an important role to generate the extreme large velocity response for a period of 2 seconds.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-529

Analysis of the high-frequency attenuation parameter from the downhole array in Taipei Basin, Taiwan

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The high-frequency attenuation parameter k, proposed by Anderson and Hough (1984) are calculated, based on the seismograms recorded by stations in the Taipei basin. The time windows applied to seismograms are suggested to be shear waves that are transformed to spectrum by the Fourier transform technique. When the frequencies are greater than a specific frequency, the spectral amplitudes decay exponentially with frequency, which can be described as $A(f)=A_0e^{-pkf}$, where A(f) is the spectral amplitude, and A_0 depends on the earthquake source and epicenter distance, f is the frequency, and the value of k is independent of frequency, unit in second. The seismograms from the downhole array in Taipei Basin deployed by Academia Sinica since 1992, provide a good opportunity to estimate the attenuation factor of the strata beneath the Taipei basin. The seismograms of 23 earthquakes with magnitude ranges of 5.1-7.1 over the period of 2003-2010 at 9 downhole array stations are taken into calculation of the k values for the shear waves. The variation of k values relative to those at the surface is calculated for each depth by means of Dk. The results show that the Dk values vary with depth and are in the range of 0.009-0.095 sec. The k values increase with earthquake magnitude at sites with code, i.e., BL, SS, TF, TU, and YH, but those decrease with earthquake magnitude at sites with code, i.e., ES and MP. In addition, The k values increase with hypo-central distance at sites with codes, i.e., BL, ES, MP, and SS, but those decrease with hypo-central distance at sites with codes, i.e., SC and TU.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-530

Evaluation of liquefaction potential analysis using different artificial neural networks models

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In the present paper analysis of subsurface soil data for prediction of liquefaction potential subjected to earthquake provokes using the Levenberg-Marquardt back propagation algorithm which is the fastest available algorithm for multi-layer perceptrons and illustrates excellent results with small training sets has been notified. A total of 112 dataset comprising mechanical and geotechnical parameters (depth, unit weight, SPT-N value, shear wave velocity, soil type and fine contents) for model A and earthquake related parameters (depth, stress reduction factor, cyclic stress ratio, cyclic resistance ratio, pore pressure, total and effective vertical stress) for model B were considered as networks inputs. The analysis was performed by use of the recorded data of Avaj-Changureh earthquake (mb 6.5, 2002, Iran) as input motion to study area respectively.

Application of try and error method and calculating the root mean square of each tested structure, showed that among the tested structures the 5-4-4-2-1 for model A and the 7-5-4-6-1 architecture for model B can be used as optimized ANN structures in this study.

To approve the applicability of proposed ANN models, the obtained results from both confirmed structures were compared with known procedures which showed good adaptabilities. The feasibility of both models was evaluated by statistical criteria that can be good evidence in network performance for prediction of liquefaction potential.

The sensitivity analysis showed that depth, shear wave velocity and SPT-N value for model A and cyclic stress ratio, cyclic resistance ratio and effective vertical stress for model B are the three important parameters in this study.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-531

A study of topographic effects on strong ground motions by 2-D Fourier Transform of terrain

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Strong ground motions are varying with respective to topography. In general, comparing to flatland, higher intensity may be found in the mountaintop and less intensity may occurred in the valley. The ground motion waveform may also changes with different topographic relief. These phenomena are called topographic effects and are quite important in ground motion prediction study.

This study present a preliminary results about the topographic effects in Taiwan by treating the topographic relief as a terrain wave. We utilized the ground motion prediction model proposed by Lin (2009) to calculate the residues from the observations of earthquake with $M_L \geq 4.5$ and 1993 to 2009. The residues of spectral acceleration (S_a) of some different periods were then obtained.

The S_a residues of some stations located in mountainous region showed that they are varying with periods. The topographic terrain waves are resolved into components of different wave numbers by 2-D Fourier transform. Based on this, the residues were correlated with some component waves. Then, the topographic effects were discussed accordingly.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-532

Earthquake Ground Motion in Sedimentary Basins: 3D Numerical Simulations, Verification and Comparison of Methods

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Lessons learned from the SCEC and ESG2006 numerical exercises led to Euroseistest Verification and Validation Project focused on the Mygdonian basin, Greece. Based on differences between 3D numerical predictions for the most realistic available basin model, we defined four canonical models of sediments overlying an elastic halfspace aiming to identify reasons for differences. Two models are 1D: 1D-sharp with three homogeneous layers and 1D-smooth with smooth velocity distribution. The 2D-sharp and 2D-smooth models are extensions of the 1D models to an asymmetric valley. In all cases, 3D wavefields include strongly dispersive surface waves in the sediments. We compared simulations by the Fourier pseudo-spectral method (FPSM), the Legendre spectral-element method (SEM) and two formulations of the finite-difference method (FDM-S and FDM-C) up to 4Hz.

The accuracy of individual solutions and level of agreement between solutions vary with type of seismic waves and depend on the smoothness of the velocity model. We found that an improper discrete representation of the interfaces can cause inaccurate numerical modelling of surface waves.

Our study underlines need for further development and verification of the numerical methods. A code that is intended for numerical prediction of earthquake

ground motion should be verified through stringent models that would make it possible to test the most important aspects of accuracy.

We present a web interface for verifying numerical-modeling methods in seismology – SISMOWINE: SeISmic MOdeling Web INterfacE, http://www.sismowine.org/. With SISMOWINE, participants can calculate solutions for the defined models using their computational method, and quantitatively and graphically compare them with those submitted by other participants.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-533

Array derived rotation of oceanic microseism measured in Ireland

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One way to measure rotational motions using classic 3-component seismometers is by applying array derived rotation (ADR). It has previously been shown that this method is suitable to extract most reliably the vertical component of rotation produced by seismic events, as well as by high frequency cultural noise (5-20 Hz). In this study, we investigate the possibility of using ADR to detect the Love waves in ocean-generated microseism.

In winter, the local oceanic noise level along the Irish coast is typically high, providing the best opportunity to test array deriving rotations in ambient noise. During the winter of 2013/2014, a temporary array consisting of 4 stations was deployed in Donegal, Ireland. The array was set up in a configuration suitable for ADR at periods around the secondary microseismic peak (~7s). If successful, the measurements of rotational motion thus obtained can combined with the transverse acceleration records from the same 4 stations. The relation between these two measurements can then be used to determine the backazimuth of sources of Love waves in microseismic noise, as well as a local phase velocity profile.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-534

Array versus point seismic rotations of local and regional earthquakes recorded at Provadia, Bulgaria

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Since August 2009, we have been operating a small-aperture array of four broadband stations in the Provadia Region (Bulgaria) known for induced seismicity connected with salt works. The array consists of three broadband stations in a triangular arrangement (side length of 90 m) and one broadband station at the central point. From June to September 2011 we deployed the six-degree-of-freedom seismic sensor Rotaphone at the central point. Collocated measurements provide an opportunity to compare rotation rate components derived from the array with those recorded by the Rotaphone. The frequency range of the array-derived rotations is limited by the sensor-separation distance up to about 6 Hz. The lowest reliable frequency on which the Rotaphone operates is 2 Hz. Regional events are of low-frequency content and the rotations obtained from them by the two approaches can be, when properly filtered, easily compared. Local records often contain higher frequencies. In this case both methods are complementary and their combination allows us to construct broadband rotational seismograms. We show several regional examples utilizing records from Central Bulgaria, Western Turkey and the Black Sea region and several examples of local events representing both microerthquakes and quarry blasts. An important application of the rotational records is the real backazimuth determination achieved by matching appropriate rotational and translational components. The results are compared to the backazimuths derived from time delays across the array.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-535

Methodology for seismic microzonation of Budapest, Hungary

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Seismicity of Budapest is moderate but somewhat higher than the average in Hungary. The largest well known historical earthquake (M5.6) that affected the city occurred in 1956 near the village of Dunaharaszti, 5-10 km distance from the southern boundary of the capital. Seismic activity is still observable in the area. The quake caused damages in Budapest that were surveyed in detail after the event. The intensity on the MSK scale reached 7 degrees in some places of south Budapest and some areas of more severe damages could be also observed inside the city.
Geological structure of Budapest is very complex. On the right bank of the Danube, older Triassic and Miocene formations outcrop to the surface while on the left bank Holocene and Pleistocene sediments cover the area.
Seismic microzonation of the city is in progress now. In the first step, applicability of topographic slope as a proxy for seismic site conditions has been studied. S wave velocity measurements have been collected and compared with the relations developed for active and passive tectonic regions. We have concluded that relation developed for active areas can be applied however numerous velocity values showed significant deviations.
Microseismic noise measurements were carried out on areas where occurrence of resonance is expected on the basis of geological maps. Besides, areas where larger damages were experienced during Dunaharaszti earthquake were also investigated. We have determined resonance frequencies and studied directivity of horizontal-to-vertical spectral ratios. We have performed MASW and ReMi measurements to determine the S wave velocities in the upper sedimentary layers and have studied the local applicability of noise cross correlation method.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-536

Estimation of spectral decay parameter (K) and shear wave quality factor (QS) using acceleration data in NW, Iran

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In this study, 22 accelerograms recorded from Ahar-Varzghan earthquakes Mw 6.5, 6.3 which occurred on 11 August 2012 in NW Iran were used. In order to determine the spectral decay parameter (k) and shear wave quality factor (Q_S) the accelerograms which have a good signal-to-noise ratio were corrected for baseline. To estimate k, the method proposed by Anderson and Hough (1984) was applied. For the first earthquake the distance dependence relationships of k are k = (0.0007)R+ 0.0284 and k = (0.0006)R+ 0.0306 for longitudinal and transverse components, respectively. Also for the second earthquake we calculated k = (0.0003)R+ 0.0513 and k = (0.0002)R+ 0.0594, for longitudinal and transverse components, respectively. These relations show that k is proportional to the epicentral distance, which is in good agreement with Anderson and Hough's (1984), and suggests ~0.05 for the zero distance Kappa factor. The shear wave quality factor Q_S can be determined by using a generalized method (Anderson and Quaas, 1988) as several investigators have done previously. The Q_S was determined in six central frequencies. We obtained a relation of $Q=66f^{0.62}$ which indicates the Q_S increases with frequency. The Q_0 value with frequency for this area has adjustment with seismotectonic of the region.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-537

Estimation of 2D shallow structure by miniature microtremor array method (cca method) for site effect evaliation

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Microtremor Array Survey is an estimation method of S-wave velocity structure by using phase velocity dispersion characteristics of Rayleigh Wave calculated array observed wave data of microtremor’s vertical components. These estimated S-wave velocity structure at each array observation site are continuously arranged along to a measurement line, it can be obtained 2D S-wave velocity structure along to this line.

Although, inversion result of S-wave velocity structure has a uncertainty, so in general, it is necessary to check the result compare with several borehole data closely located at the site. But it is not so easy to obtain a suitable borehole data in neighborhood. In such case, a pre-analysis method is suggested by using simplified profiling method (SP Method) which can be obtained an image of S-wave velocity structure by applying a simple transform equation to phase velocity dispersion characteristics. The imaging result by SP Method is not so clear but it’s objectively useful for understand the S-wave velocity structure.

In this research, we tried to use the miniature microtremor array observation method (Senna et al., 2012) and estimated the S-wave velocity structure by using SP Method adding the information of soil discontinuity due to basement layer of underground structure applied simplified method which the frequency of H/V spectra (Nakamura, 1989) converted to depth by picking up the peak and trough (called as Peak Method or Trough Method) as a discontinuity of soil structure. Finally, we estimated 2D shallow underground structure of Hadano Basin, Kanagawa Pref. Japan. We can confirm the applicability of above mentioned

miniature microtremor array method.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-538

Benchmarking numerical simulation of 1-D nonlinear site response: Preliminary results from the PRENOLIN validation phase on real sites.

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The main objective of the PRENOLIN project is the assessment of uncertainties associated to nonlinear simulation of 1D site effects, through a benchmark of several wave propagation codes having different nonlinear soil constitutive models, applied to the same soil columns. After a verification phase (i.e. comparison between numerical codes on idealistic, simple cases), the ongoing validation phase compares numerical predictions with actual strong motion recordings at two well-known sites in Japan (KSRH10 and Sendai). The benchmark involves 24 different teams and 28 different nonlinear computations, performed in total stress for sake of simplicity.

KSRH10 is a deep sedimentary site while Sendai is much shallower (down-hole sensor at 250 and 8 m depth, operated by Kik-net and PARI, respectively). Both in-situ and laboratory measurements were performed to define the soil columns: Vs, Vp, density, PI, non-linear degradation curves for each kind of soil. The down-hole and surface recordings were selected as input and target motion, respectively. Ten recordings were considered for each site, spanning a wide range of PGA values.

The computed amplification is found to be generally higher than observed data for weak motion. This could come from a too low attenuation, or an overestimation of the destructive interference effects at depth, linked with the assumption of vertically incident plane S-waves. Conversely, the computed nonlinear soil response is found generally lower than the recorded data for strong motion recordings. The last, ongoing phase of this benchmark is thus a reinterpretation of the laboratory measurements by each team, for an optimal tuning to their own

constitutive model. Another explanation of the discrepancy could be associated with pore pressure effects.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-539

Shallow structure, basament depth and ground predominant period variation in Vina del Mar (Chile)

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Historical and recent damaging earthquakes (1906, 1985, 2010) showed similar building damage distribution in Viña del Mar city. This work analyses the influence of both shallow ground structure and basement depth differences on the predominant periods and amplification variations of ground motion in different sites of the flat area of the city. A detailed analysis of geological and geotechnical data from 60 borehole sites and NSPT measures in other 62 sites of the Viña flat area has allowed us to obtain the surface ground structure up to a depth of 10, 20 and 30 m in 122, 58 and 23 sites, respectively. According to VS30 classification of EC-8 soils of the plain are type C (D in the IBC and NCh433 codes). The predominant period (Tp) estimate from ambient noise records (with the HVSR technique) in 84 points regularly spaced (? ~200 m) in the plain city area (on Quaternary sediments) are between 0.4 and 1.1 s. Tp values are well correlated with the basement depth (obtained from gravimetric data) but are far from those estimated from VS30 data. Ground transfer functions estimated in different sites from local strong ground motion records and by computing the 1-D response of the shallow structure show similar Tp values to those obtained from microtremor. VS30 estimates of the mean seismic amplification gives small differences among sites, but appreciable differences are found with the other methods mentioned above.

IASPEI (Seismology, Geophysics)

S06dp - S06d/S06e Strong Ground Motion: Site Effects and Rotational Seismology

S06dp-540

Estimated ground motion in adra town (SE Spain) due to january 4th, 1994 local event

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The shear-wave velocity structure of unconsolidated materials in Adra town was jointly evaluated by means of the inversion of Rayleigh wave dispersion curves obtained from ambient noise array records at four open sites (using SPAC method) and from MASW profiles, 3.4 km of linear transects conducted through the streets of town. VS structures allowed a soil classification map of Adra town based on the VS30 values, according with Eurocode EC-8 types. The average shear-wave velocity at different depths has been mapped to show its spatial distribution. Synthetic seismograms were computed in each site based on shear-wave velocity structures and taking as input the strong motion record on rock at Adra station of the January 4th, 1994 (Mw 4.9) event. The severity of this event at Adra town has been quantified through the estimates of earthquake engineering parameters: peak ground motion (PGA, PGV) and Arias intensity (AI). The PGA values range between 150 and 350 gal, being higher ones (>250 gal) located in the southern part of the town, on recent alluvial deposits. PGA amplification factors (AF) were calculated as the ratio between the PGA values of the synthetic seismograms and the value at Adra station record. The spatial distribution of AF reveals a general increasing trend from 1.2-1.7 in northern and western areas (on bedrock) to 2.2-2.7 at the southern zone (on soils). The AF and PGA, PGV and AI distribution maps are able to explain the damage distribution caused by the 1994 Adra earthquake.

IASPEI (Seismology, Geophysics)

S07a - S07 Seismic Hazard and Risk

IUGG-2291

Renewal probabilistic seismic hazard assessment for Myanmar

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To assess renewal probabilistic seismic hazard for Myanmar, we developed an approach and implemented the state-of-the-art parameters of the seismogenic sources in this region. Based on the information on tectonic setting, geology, geomorphology, and earthquake catalog, four seismogenics sources were identified. Those are: (a) the Sagaing Fault, (b) the Shan Plateau, (c) the Indo-Burma subduction interface, and (d) subduction intraslab. For the treatment of time-dependency, the approach incorporates impacts during both long-term and short-term periods. For long-term period, the Brownian Passage Time (BPT) model illustrates earthquake probability for sources by considering occurrence time of past events and recurrence intervals. For evaluation of short-term rate change, we investigated earthquake interactions between sources in form of stress change. An increased stress state promoted occurrence of consequent events, while stress decrease inhibits future seismic activity. Through considering ground motion prediction equations for different types of sources and site conditions, renewal probabilistic seismic hazard was assessed. The seismogenic sources with short recurrence intervals or/and long elapsed time of the last events result in high seismic hazards. The renewal hazard map can be updated upon occurrence of a significant event.

IASPEI (Seismology, Geophysics)

S07a - S07 Seismic Hazard and Risk

IUGG-2388

Canada's 5th Generation Seismic Hazard Model for the 2015 National Building Code of Canada

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Canada's 5th Generation seismic hazard model has been developed to generate seismic design values for the 2015 National Building Code of Canada (NBCC2015). The model updates the earthquake catalog, consistently expresses earthquake magnitudes in terms of moment magnitude, revises earthquake source zones, and includes probabilistic treatment of Cascadia and other fault sources, all so as to estimate mean ground shaking at the 2% in 50-year probability level. Hence it takes advantage of newer knowledge and replaces the 4th Generation 'robust' combination of alternative models used for NBCC2010 (for example, the hazard in southwestern BC was the higher of the H-probabilistic, the R-probabilistic or the Cascadia deterministic model) by a fully probabilistic model. The ground-motion prediction equations (GMPEs) used (Atkinson and Adams, 2013 CJCE) represent a major advance over those used for the 4th Generation. Seismic design values (on Soil Class C at Vs30=450 m/s) for PGA, PGV and for Sa(T) for T = 0.2, 0.5, 1.0, 2.0, 5.0, and 10.0 s will be used in NBCC2015. Values for the longer two periods are possible because of the newer GMPEs, and they replace the ½*Sa(2.0) value used for T>4 s in 2010. Seismic hazard results will be presented, and key differences from NBCC2010 discussed. In general, for locations in eastern Canada, the seismic hazard at long periods has increased while the seismic hazard at short periods has decreased - in some places significantly. For locations in western Canada, the seismic hazard at long periods has increased significantly for areas affected by great Cascadia interface earthquakes. In Haida Gwaii and the Yukon, the explicit inclusion of fault sources has also affected the estimated hazard.

IASPEI (Seismology, Geophysics)

S07a - S07 Seismic Hazard and Risk

IUGG-3711

The 2014 Update of the United States National seismic hazard models

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During 2014-2015 the USGS updated the U.S. National Seismic Hazard models for the lower 48 states and began developing new products to better communicate with end-users. The seismic hazard assessment is based on the best available science at the time of the update, and incorporate a broad range of new datasets, models, and updated input parameters. We implemented several new changes. For the Central and Eastern U.S., we implemented a new moment magnitude (Mw) catalog, updated the maximum-magnitude distribution, updated the smoothing algorithms for estimating earthquake rates away from faults, and modified the sizes and rates of New Madrid Seismic Zone earthquakes. We also updated the model for induced seismicity triggered by manmade activities. In the Intermountain West, we implemented new smoothing algorithms, fault geometries for normal faults, multiple Wasatch fault alternatives, and fault slip rates based on models obtained by inverting geodetic and geologic data simultaneously. For the Pacific NW, we developed new Cascadia fault rupture models that incorporate additional earthquakes in the south and modified the crustal fault model. For California, we implemented the new UCERF3 source model that is based on new deformation models, relaxes segmentation assumptions, and includes multi-fault ruptures. We also applied several new ground motion models for shallow crustal earthquakes, subduction interface, and deep earthquakes. The improvements in input models resulted in small changes across most of the country, but have caused significant changes up to ± 25% at 1 Hz and 5 Hz spectral accelerations in localized areas.

IASPEI (Seismology, Geophysics)

S07a - S07 Seismic Hazard and Risk

IUGG-5194

Pshab: Probabilistic seismic hazard analysis for Brazil, a national map building effort

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GSHAP [Giardini et al.; Shedlock and Tanner, An.Geof.,1999] is the latest well-known hazard map covering Brazil. GSHAP shows moderate hazard levels in northeastern Brazil (e.g., 0.2g for PGA at 10% poe in 50 years), extremely low hazard in the rest of the country, and an increase at the western border due to Andean seismicity. The other known model based on zones, smoothing and neotectonic faults [Petersen et al., USGS, 2010] is still being developed and was not considered yet for the present Brazilian building code [ABNT, 2006] which was heavily based on GSHAP results [Santos & Lima, 14WCEE, 2008], and lacks information on other intraplate seismicity areas known to be active as the northeastern region. Motivated by the GEM-SARA project (Global Earthquake Model - South America Risk Assessment), this work presents the effort from Brazilian seismologists to update and increase the resolution of previous results using the newest catalogue and the seismic source characterization as defined by the Brazilian seismological community.To this aim we: (a) updated the Brazilian Earthquake Catalogue [Braz.Seismic.Bull., version 2014.11, IAG-USP], homogeneized in moment magnitude; (b) developed various source models (area source and smoothed seismicity models), based on different expertise groups; (c) compiled all available strong motion records and processed them in an homogeneous way;(d) developed the source models and GMPEs logic-trees based on the previous results; (e) finally computed PSHA using the OpenQuake software [Pagani et al., SRL, 2014], in order to produce hazard curves and maps for Brazil for rock soil condition.The models and results will be publicly available under CC-BY license.

IASPEI (Seismology, Geophysics)

S07a - S07 Seismic Hazard and Risk

IUGG-5662

New probabilistic seismic hazard analysis for Ecuador

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For the last seven years a team of French and Ecuadorian scientists have systematically addressed the different aspects of PSHA for the Ecuadorian territory. As a first step, the seismic history of the country was reviewed and the seismic parameters for 30 events spanning five centuries were determined using the Bakun & Wenthworth and bootstrap resampling methodologies. Then, the instrumental seismicity available in local and international catalogs since the beginning ot the 20th century was carefully reviewed and merged in a single unified and homogenized catalog by means of a prioritizing scheme. Once the historical earthquakes were appended, this catalog constitutes now the reference for PSHA studies in the country. A new seismic source zone model has been developed on the basis of a thorough review of the geodynamics and seismotectonics of NW South America. This new model consists of 19 source zones and outdates the previous seismic source zonation used in 2011 to calculate the seismic hazard map of Ecuador in the frame of the 2011 Ecuadorian Building Code. Since in Ecuador there is still not a strong motion database that could be used with confidence for generating local GMPEs, worldwide data equations for similar tectonic environments were used for PSHA calculations using the OpenQuake engine. The first results show that the seismic hazard for a 475 yr return period is highest on top of the subduction source zones, but clearly demonstrate too that the shallow continental crust sources are also high and significantly influence the hazard in their surroundings.

IASPEI (Seismology, Geophysics)

S07b - S07 Seismic Hazard and Risk

IUGG-2370

Are apparent Mmax differences between different superdomains in Stable Continental Regions real?

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A popular method to assess Mmax, the upper truncation of the magnitude-frequency distribution, in distributed-seismicity sources is the Bayesian Mmax approach (EPRI, 1994; USNRC, 2012). In this approach, a global prior distribution on Mmax was established for stable continental regions (SCR) based on magnitudes of earthquakes observed worldwide within tectonically similar domains, grouped into so-called superdomains. This prior distribution is multiplied with a source-specific likelihood function that depends on the largest magnitude and the number of earthquakes observed in the source, to obtain a posterior distribution on Mmax that is treated as epistemic uncertainty in PSHA. However, in many SCR areas the sample size is low, as a result of which the posterior distribution depends strongly on the Mmax prior. Thus, the choice of a prior distribution is critical in estimating Mmax. We investigate the nature of the observed superdomain Mmax distribution that was used to derive the Mmax prior, and test if it could also be explained by a uniform SCR Mmax, given our limited periods of observation. Using recurrence parameters derived per continent, catalog completeness thresholds for different regions within each continent, and assuming a Poisson temporal occurrence model, we simulate 10,000 random catalogs for each SCR domain, combine them into superdomain catalogs, and determine the largest sampled magnitude and the number of sampled earthquakes in each. With a parent Mmax of 7.9, the largest observed magnitude in SCR, we obtain superdomain Mmax distributions that are very similar to the one observed. We also investigate the effect of larger parent Mmax and longer catalogs. Our results confirm that catalog length is indeed the limiting factor in our knowledge of Mmax.

IASPEI (Seismology, Geophysics)

S07b - S07 Seismic Hazard and Risk

IUGG-2760

Bipartite earthquake magnitude-frequency distributions

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It is usually assumed in probabilistic seismic hazard assessment that earthquakes occurrence can be described as a Poisson process, with a log-linear relationship between magnitude and cumulative frequency. While it is likely neither assumption is true at the level of single faults, they are generally good descriptors of aggregate earthquake behaviour over large areas. There are occasions, though, when the Gutenberg-Richter magnitude-frequency distribution fails to model seismicity adequately even in a substantial seismic source zone. Attempts to force a simple linear fit results in an unrealistic model. Assumptions that the problem is due either to catalogue incompleteness or statistical flukes can be shown to be untenable. Examples are given from the SHARE project for both active and intraplate regions (Italy and the UK). It appears that in such cases there are in effect two earthquake populations, small and large events, and the occurrence rate of the one cannot be estimated from the other. This can be handled in conventional probabilistic seismic hazard assessment by modelling a problem seismic source twice with the same geometry, once for each population.

IASPEI (Seismology, Geophysics)

S07b - S07 Seismic Hazard and Risk

IUGG-4159

Understanding the earthquake source model for large-scale seismic hazard models: The middle east region

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The Middle East region is located at the junction of major tectonic plates, namely the African, Arabian and Eurasian plates, resulting in very high tectonic activity. Some of the destructive earthquake occurred in the Middle East, affecting most countries in the region, including Turkey, Pakistan, Iran, Egypt, and Armenia, hence the need of quantitatively estimate the seismic hazard is a continuing concern. In this light, the Earthquake Model of the Middle East Region (EMME) project was successfully established under the Global Earthquake Model umbrella to deliver a harmonized seismic hazard and risk assessment for the Middle East region.

For such geographic large-scale region, the probabilistic approach was considered by the EMME experts to evaluate the ground-shaking hazard. Within this framework, the earthquake source model (ESM) resulted from harmonizing the available tectonic, seismogenic, paleoseismic, geological data and alternative interpretation of seismological information. The ESM was developed to represent the earthquake occurrence rates and to describe the individual seismic source properties following state-of-the-art procedures.

We are presenting the ESM's anatomy, starting with the main assumptions, following the description of the supportive datasets - earthquake catalogue, tectonic regionalization and active faults. We will further focus on definition and delineation of the main seismic source models and intrinsic uncertainty in the earthquakes occurrence rate estimation. Finally, we will underline the inherent limitations of the EMME earthquake source model, as used to probabilistically evaluate the ground-motion hazard in the region of interest: the Middle East.

IASPEI (Seismology, Geophysics)

S07b - S07 Seismic Hazard and Risk

IUGG-4367

The global seismic hazard assessment program (GSHAP) legacy

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Global Seismic Hazard Assessment Program – or simply GSHAP, when launched, almost two decades ago, aimed at establishing a common framework to evaluate the seismic hazard over geographically large-scales, i.e. countries, regions, continents and finally the globe. Its main product, the global seismic hazard map was a milestone, unique at that time and for a decade have served as the main reference worldwide. Today, for most of the Earth's seismically active regions such Europe, Northern and Southern America, Central and South-East Asia, Japan, Australia, New Zealand, the GSHAP seismic hazard map was updated. The rapid increase of the new data, advance on the earthquake process knowledge, technological progress, both hardware and software, contributed all in updates of these regional seismic hazard models.

We present herein, a short retrospective overview of the achievements as well as the pitfalls of the GSHAP. Further, we will focus our attention on the next generation of harmonized seismic hazard models, as elaborated within the Global Earthquake Model, regional programs: the 2013 European Seismic Hazard Model, the 2014 Earthquake Model for Middle East, and the 2015 Earthquake Model of Central Asia. We summarize some of the main characteristics of these models, and illustrate examples of newly developed datasets, fully harmonized across national borders for the first time after the GSHAP completion.

IASPEI (Seismology, Geophysics)

S07b - S07 Seismic Hazard and Risk

IUGG-4449

Probabilistic seismic hazard assessment (PSHA) for Ethiopia and the neighborhood

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A new probabilistic seismic hazard assessment (PSHA) is conducted for the Horn of Africa region using CRISIS2012 software, from instrumental earthquake catalogue, with the intent of revising the building code of Ethiopia and the neighborhood. Earthquake magnitude is homogenized to Mw. 13 area sources are considered as inferred from fault plane solutions in the region which thought to be tectonically distinct. The catalogue is declustered using Gardner and Knopoff (1974) algorithm. The Kijko and Smit (2012) approach of treating multiple earthquake catalogues with different level of completeness is implemented for the 13 area sources whenever possible to create a homogeneous data set. Chiou and Youngs (2008) attenuation model is employed.

The 10% probability of exceedance in 50 years in the spatial window of 0°N to 20°N latitude and 30°E to 50°E longitudes varies between 0 to 0.18g PGA values. The values for this draft result are lower than previous estimates in the region which could be due to the declustering of the catalogue. However, the achieved results are consistent with seismotectonics of the region. As developing earthquake hazard model is a process, incorporating other hazard inputs will improve the map and hence further investigation is required.

IASPEI (Seismology, Geophysics)

S07c - S07 Seismic Hazard and Risk

IUGG-0565

Computing seismic loss estimates within a big city, using open-source solutions. Bucharest case study.

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The seismic risk analysis of big cities is a very demanding yet necessary task; the modeling of such a complex environment requires first of all insightful input data at a good resolution, referring to local effects, buildings, their residents and economical aspects. Until recent, these data was unavailable for Bucharest, one of the most endangered capital city in the world due to seismic hazard. Based on the 2011 buildings and population census, on actual Vrancea hazard studies including a microzonation map based on nonlinear approach and through the use of earthquake loss estimation software like SELENA and ELER (both using analytical methods), we developed a methodology that computes for the first time (also in near real time) residential building damage and corresponding socio-economic losses for 128 areas defining the entire city. The approach relies on the classification of buildings into 48 categories with specific vulnerability curves, on using the improved displacement coefficient method and on modeling the damage implications in terms of socio-economic impact.Due to the desired impact on society of the analysis we assess the best practices of representing the output, respecting the needs of disaster management institutions. Expert judgment is used behind the maps integrated within a GIS.In order to compare the results with real losses we use scenarios for the 4 march 1977 Vrancea earthquake (Mw 7.4, H 94 km) that produced 1424 deaths and 7598 injuries in Bucharest. The observed fit is, although undesirable, within the expected range.Even though the analysis is closely related to the Bucharest specific, we provide a generally applicable methodology and concept that can lead to the implementation of the schema within other big cities.

IASPEI (Seismology, Geophysics)

S07c - S07 Seismic Hazard and Risk

IUGG-2138

Identification of risk of soil-building resonance for strategic public buildings in Dubrovnik-Neretva County (Croatia)

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One of the most important factors in mitigating seismic risk is identification of buildings which will result the weakest under the seismic shaking using the resonance approach. If the soil resonance frequency is close to those of buildings, soil-building resonance can occur which can cause severe structural damage or collapse of the building. It is also well known that resonance phenomena can have great influence on the spatial distribution of damage caused by destructive earthquakes. Dubrovnik-Neretva County is the region with the highest defined seismic hazard in Croatia. Therefore, in the scope of HOLISTIC Seismic and Wildfire Risks IPA project, estimation of dynamic parameters (fundamental period and damping coefficient, building response spectra) will be done for at least 30 strategic public buildings in the County, by performing measurements of building vibrations induced by ambient noise. Estimation of soil fundamental frequency will be done using the microtremor measurements in the free-field near the buildings. Based on these measurements, buildings with their natural frequencies close to the foundation soil resonance frequency will be identified as the ones that are in danger of the soil-building resonance during future earthquakes. In one of these buildings continuous instrumental monitoring will be performed by a broad-band sensor for the time period of at least six months in order to continuously monitor the variation of its dynamic parameters caused by environmental factors or earthquakes. Here we present preliminary results obtained in the measurement campaign of February-March 2015.

IASPEI (Seismology, Geophysics)

S07c - S07 Seismic Hazard and Risk

IUGG-2639

Investigating the impact of a more advanced method for ground motion modeling in earthquake damage and loss assessment

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An important component and input parameter in earthquake damage and loss assessment (often referred to as seismic risk) is the seismic hazard represented in terms of earthquake ground shaking. Although it is well known that rupture kinematics plays an important role for the spatial distribution and characteristics of ground shaking and hence the associated damage, seismic risk studies have traditionally been based on simple models often considering a point/line source in combination with empirical ground motion prediction equations (GMPE). In this study, an alternative approach for earthquake damage and loss assessment is suggested, where the ground shaking is determined through stochastic ground motion simulations. To account for uncertainties in the source parameters for future earthquakes, realistic ranges of input parameter values are defined through calibration with information on ground motion records of past events, and a large number of simulations are performed to cover these ranges. The method is applied to the city of Managua, Nicaragua, which is underlain by several surface-rupturing active faults of various types. Results are presented both in terms of ground shaking and associated damage and loss estimates, and are compared to the results of the traditional GMPE-based approach.

IASPEI (Seismology, Geophysics)

S07d - S07 Seismic Hazard and Risk

IUGG-0262

Seismic characteristics and seismic hazard assessment: Source region of the 1905 great Kangra earthquake Mw 8.0 in western Himalaya

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Seismicity and seismic characteristics like b-value, fractal dimension, energy release and recurrence period are assessed for a circular region of radius 500 km in the epicenter area of the 1905 great Kangra earthquake Mw 8.0 in western Himalaya. The region also includes epicenters of the 2005 Kashmir earthquake, the 1991 Uttarkashi and the 1999 Chamoli earthquakes. The International Seismological Centre catalogue earthquakes Mb ≥ 3.8 for the period 1964-2011 are used. The b-values are estimated using the Maximum Likelihood Method , Least Square Method and the new alternative Kaltek method. The fractal dimension is estimated using the correlation integral method. The events are also used for estimating radiated energy in the region. The probability of occurrence of moderate earthquakes (Mb ≥ 5.0) during a specified interval of time has been estimated on the basis of four probabilistic models namely, Poisson, Weibul, Gamma and Lognormal. The model parameters have been estimated by the Maximum Likelihood Estimates. It is found that there is a 99% probability for occurrence of at least one earthquake of magnitude Mb ≥ 5.0 and Mb ≥ 5.5 in this region in a time window of three–four years and eight-nine years respectively from the year 2011. The b-value maps have identified the variable stressed zones, and the fractal dimension maps the fractal characteristics of the active fault zones. The energy release map identified the zones of higher and lower energy release, thus indicating the areas of future probable earthquakes. The vulnerable source zones identified by these maps are corroborated with the probabilistic models to assess the seismic hazards in the region.

IASPEI (Seismology, Geophysics)

S07d - S07 Seismic Hazard and Risk

IUGG-0409

The effects of February 3, 2008, earthquake in the lake Kivu Basin, Western Branch of the East-Africa Rift Valleys system

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The Lake Kivu basin had experienced an earthquake of local magnitude ml= 6.0 on February 3, 2008 at 7h34' UT, in its south-western part at 10 km depth. Many phenomena were generated in the Lake Kivu and on the shorelines. At several places were observed land subsidence on the shoreline where several children were killed in D.R. Congo and Rwanda sides. At other places land uplift was observed. According to the fishermen, small tsunami was generated and attacked the coast lines. The highest level accessed by the tsunami was estimated to 4m at Ibindja Island. The small gas escaping generated by the tsunami was observed at several places in the Lake Kivu. Many damages were recorded in Bukavu city and surrounding areas in D.R. Congo and Rwanda, characterized by the fissures on the walls or collapse of houses. Total 49 people were killed by the earthquake and aftershocks, more precisely 10 in D.R.C. and 39 in Rwanda. This event was preceded by many foreshocks and followed by a long duration of felt aftershocks up to June 2008. The hypocentre distribution was mainly concentrated in the eastern part of the epicentre of the main event. The main aftershock occurred on February 14th, 2008 at 10 km depth. The main shock was associated to the fault in the NNE-SSW direction. The focal mechanism solution of this event indicates a normal fault. The maximum intensity was recorded close to the epicentre area and estimated to VIII-IX.

IASPEI (Seismology, Geophysics)

S07d - S07 Seismic Hazard and Risk

IUGG-1836

Rupture Process of the M7.2 October 2013 Bohol Philippines Earthquake

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The island of Bohol, in central Visayas, Philippines, endured a devastating earthquake of magnitude 7.2 in the morning of October 15, 2013. This inland earthquake occurred as a result of movement along a newly-discovered fault zone named the North Bohol fault. Global Centroid Moment Tensor solutions for the mainshock and several aftershocks revealed a thrust fault focal mechanism, in agreement with the compressional deformation observed in the region. PHIVOLCS mapped a surface trace approximately 6 km with vertical offsets estimated at 2 to 5 m, in the municipality of Inabanga, northwest of Bohol. Ground uplift observed in Maribojoc and Loon, which shifted the shoreline for about 50 m seawards, is thought to represent the southern end of the rupture. Hundreds of aftershocks ensued months after the main event, the epicentres of which aid in constraining the ruptured fault zone that may extend up to 50 km in length. Notable in this event is the strong ground shaking that caused enormous structural damage to Bohol's built environment. The event also featured secondary hazards including sinkholes, landslides, liquefaction, lateral spreading and coastal uplift and subsidence. In this study, the intention is to develop a robust source model using multiple datasets like seismic waveforms, satellite radar images and GPS observations, and to assemble a comprehensive damage survey dataset. Seismological and engineering attributes of the Bohol earthquake are the salient points of this research. The rupture model combined with analysis of damage data will demonstrate the usefulness of source characterization in constraining the fragility curves and vulnerability models.

IASPEI (Seismology, Geophysics)

S07e - S07 Seismic Hazard and Risk

IUGG-1644

How can the world learn the lesson from Tohoku Earthquake? : Epistemic uncertainty aspects

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An M=9 class earthquake had never been considered in the Japanese Seismic Hazard Assessment (SHA) until the 2011 Tohoku-oki M=9 earthquake occurred. Tohoku (northeastern Hoshu, Japan) was one of most investigated subduction zones in the world where many earthquake reoccurrence cycles discovered and therefore a renewal model of Brownian Passage Time (BPT) was applied to SHA. Seismologists became deeply aware of the SHA's complexity and uncertainty. In order to reduce epistemic uncertainties, several discussion models (J-SHIS, 2012, 2013) have been carried out over three years to enrich the epistemic for the SHA.

In the East Japan subduction zone, the maximum potential earthquake magnitude was under-estimated by the previous PSHA map. To deal with this complicated issue, we have been working for the reconsiderations of different seismic models with uncertainties in SHA.
This paper presence discussions of: 1) Re-examination of intensity distribution during the Tohoku earthquake; 2) Low probability of earthquakes in long-term return periods; 3) Preparation of "Big Earthquake".
We do think what happened in Tohoku most likely occur in the other seismic zones where knowledge may be absent. With the common motivations and missions of mitigation seismic hazard and risks, NIED joined Global Earthquake Model (GEM) Foundation as a representative of Japan to reinforce the public part of GEM's partnership in 2012. We eager to collaborate with public institutions and GEM regional programs to carry on works for a harmonization SHA map in the East Asia region as well as the Asia region.

IASPEI (Seismology, Geophysics)

S07e - S07 Seismic Hazard and Risk

IUGG-2010

Hazard assessment of critical facilities: earthquake database compilation

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Seismic hazard assessment is mandatory requirement for critical facilities in many countries. The IAEA considers compilation of the comprehensive earthquake database as the first order task in seismic hazard assessment for NPP. However sometimes, database compilation is treated as a routine technical procedure; meanwhile the result strongly depends on this stage of work. No sophisticated statistical analysis or (and) generation of synthetic catalogue is able to compensate completely and reliably the lack of high quality data on earthquakes. The study presents materials and summarizes the experience accumulated by the Institute of Physics of the Earth (Moscow) in seismic hazard assessment of pipelines in Siberia, Altai and South-East Europe (Serbia). Comprehensive databases have to include information related to a wide range of magnitudes and space and time scales, starting from the local high resolution instrumental networks up to paleoseismic data. Before entering the database each data type has to be critically examined. One should be very careful to avoid mixing different data types at too early stages of the database compilation.
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IASPEI (Seismology, Geophysics)

S07e - S07 Seismic Hazard and Risk

IUGG-3553

Seismic hazard and risk assessment based on unified scaling law for earthquakes: Thirteen principal urban agglomerations of India

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The confirmed fractal nature of earthquakes and their distribution in space implies that traditional probabilistic estimations of seismic hazard and risks for cities and urban agglomerations are usually underestimated. The evident patterns of distributed seismic activity follow the Unified Scaling Law for Earthquakes, USLE, which generalizes Gutenberg-Richter recurrence relation. The results of the systematic global analysis imply that the recurrence of earthquakes in a region is characterized with USLE: $\log_{10}N(M, L)=A+B\times(5–M)+C\times\log_{10}L$, where N(M,L) - expected annual number of earthquakes of magnitude M within an area of liner size L, A determines seismic static rate, B - balance between magnitude ranges, and C - fractal dimension of seismic loci.

We apply the seismic hazard and risk assessment methodology developed recently to thirteen urban agglomerations of India. The approach is based on USLE, pattern recognition of earthquake-prone geomorphic nodes, and neo-deterministic scenarios of destructive ground shaking. Objects of risk are individuals (i) as reported in the 2010 National Census data and (ii) as predicted for 2010 by Gridded Population of the World (model GPWv3); vulnerability depends nonlinearly on population density. The resulting maps of seismic hazard and different risk estimates are cross compared. To avoid misleading interpretations, we emphasize that risk estimates presented here for academic purposes only. In the matter of fact, they confirm that estimations addressing more realistic and practical kinds of seismic risks should involve experts in distribution of objects of risk of different vulnerability, i.e., specialists in earthquake engineering, social sciences, and economics.

IASPEI (Seismology, Geophysics)

S07e - S07 Seismic Hazard and Risk

IUGG-3567

Strain rate and stress field of Switzerland

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We use geodetic and seismic datasets to check whether the surface deformation and the seismic activity are in agreement in terms of moment release and stress/strain orientations within the territory of Switzerland. We find that for most of the country, the stress released is consistent with the lithosphere deformation measured by the Global Positioning System (GPS). The surface strain rate ($<5.0\ 10^{-8}$ /yr) fits well with an average stress rate release of $\sim 2.0\ 10^{11}$ Nm/yr, however, displays few agreement with long-term (and deep) deformation. For three regions, we find seismic activity and surface deformation not to be in agreement. In the Basel area, deep seismicity exists while surface deformation is absent. This situation is contrast to what is found in the Ticino and the Swiss Jura, where the seismic activity is absent but surface deformation is detected ($\sim 2\ 10^{-8}$ /yr). From surface strain rates, assuming that the entire accumulated strain over the last 120y is released seismically, we estimate the potential for a magnitude M_W 5.7 with very few seismicity detected in the Ticino while with the same strain rates in the Valais, seismic activity is abundant with historically documented destructive earthquakes.

IASPEI (Seismology, Geophysics)

S07e - S07 Seismic Hazard and Risk

IUGG-4734

Including foreshocks and aftershocks in time-independent probabilistic seismic hazard analysis for Italy

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Although the standard seismicity models require a declustered earthquake catalog of independent events for calculation of time-independent earthquake rates, recent studies have shown that the declustering may lead to a significant underestimation of the true hazard. Therefore, in this study we attempt to incorporate foreshocks and aftershocks into the time-independent seismic hazard analysis considering that the mainshock and each of its associated aftershocks have an opportunity to exceed a given amount of ground motion at a site. In order to incorporate clustered events into time-independent seismic hazard analysis we use the procedure proposed by Marzocchi and Taroni (2014) in which uses a gamma factor to correct for the missing rate due to declustering in the catalogs. First we calculate the rate using declustered catalog then obtain the new clustered seismicity rates multiplying by a factor in a way that the total seismicity rate matches to the whole observed seismicity rate. In this way we are assuming that each cell of the grid has similar clustering properties. In our case we compute corrective factors for the Gardner and Knopoff (1974) and the Reasenberg (1985) declustering algorithms in which are applied to the both historical CPTI11 and instrumental CSI1.1 Italian catalogs. The earthquake rates determined for the cells (0.1 degree in latitude and longitude) are spatially smoothed using a two-dimensional spatial Gaussian function with isotropic correlation distance. The seismic hazard calculated using the clustered catalogs leads to increased rates of exceeding ground motions in PGA at 10% probability of exceedance in 50 years.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-313

Identification of liquefiable soil layers by a proposed geotechnical based procedure- A case study

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Liquefaction is one of the most important phenomena triggering by an earthquake and have been widely observed during numerous devastating earthquakes. It can cause catastrophic failure to infra structure such as earth dams in a very short period of time, which could lead to loss of life and large economics damages.

Several earth dam were affected by happened earthquake in Iran and therefore better knowledge on liquefaction behavior of this type of structures because of providing emergency supplies and ensure structural safety in engineering terms are so important.

In this study on base of a developed C# graphical user interface computer code, a geotechnical based procedure using the standard penetration test data of 16 drilled boreholes with maximum depth of 60m and obtained results from field and laboratory investigations, were proposed and applied to Nematabad embankment dam in the west of Iran and an estimation of the liquefaction behavior subjected to Avaj-Changureh earthquake (2002, Iran) vibrations with a careful assessment of the involved parameters has been carried out. To validate the procedure, a detailed comparison between the results of this study with those obtained by known accepted procedures was conducted. The results showed the applicability of the employed procedure whereas it provided suitable compatibility regarding the accepted ones. The analyzed data indicated that the layers in depths 0 to 8, 16, 22 and 45m from subsurface are susceptible for liquefaction behavior under the applied earthquake and by a greater seismic event it may be liquefied.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-314

Towards a system with real-time capabilities for the analysis of risks generated by road networks after major earthquakes

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Each major earthquake has the capability to produce a large amount of damage with a wide extent, in a very short amount of time. Out of the total, a very significant percent is for indirect losses. The transportation networks have an essential role – both immediately after an earthquake, and also long time before it occurred; they constitute support for the fast intervention and for the recovery efforts. Therefore, their functionality and capability to satisfy the demands is a key aspect in reducing human and economic losses. By modeling the behavior of road networks right after an earthquake, precious estimates about the impact of bottlenecks (like bridge or tunnel collapse, traffic or debris jams) can be obtained, leading to quick and prioritized intervention. We aim to define and test a system able to automatically compute this information, in a GIS environment that allows the valorization of the spatial dimension. The near real-time capability relies on the possibility to use ShakeMap like maps with parameters like PGA or MMI. These parameters serve as input in the analysis of structures through fragility curves or analytical methods like MADRS or I-DCM for buildings, and as weight factors in economical or social behavior models. Based on a selection of fit methods previously developed, on the ArcGIS Network Analyst Toolbox capabilities and on new research of the link between direct and indirect damage we define a methodology that provides answer to key questions like: „What road segments are critical in case of an earthquake?” or „What are the intervention times in case of an earthquake?”. Furthermore, we test an urban scenario and explain how free online data for road network definition, traffic values or other aspects can be processed for the methodology.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-315

Reassessment of active faulting in the Zanjan region (northwest Iran) using geomorphic and geophysical investigations

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Active tectonics in NW Iran, including the Zanjan region, is due to the continental convergence of the Arabian and Eurasian plates. In several regions (e.g., Zagros and Alborz), active deformation is expressed by moderate to high rates of seismicity, while, in other domains such as the Zanjan region, this rate is extremely low. In such regions a realistic evaluation of active faulting is of great importance to assess seismic hazard and its social impacts.

The Zanjan region is the transition between two opposing crustal-scale tectonic movements. In the east side, South Caspian Basin moves southwest relative to central Iran. This motion is accommodated by NW-striking sinistral faults. In the west side, the SW-ward motion of NW Iran relative to central Iran is mainly taken up by NW-striking dextral faults. In the absence of earthquake data, activity of geological structures becomes crucial in evaluating seismic hazard in this region. Our knowledge of active faulting in the region is limited to fault traces mapped mainly based on remote sensing observations.

We have surveyed a main sector of the Zanjan fault network using magnetic and geo-electric geophysical surveys along with direct and remote geomorphic investigations. This led us to distinguish erosional features from geomorphic landforms related to Quaternary faulting, and consequently, to revise the active fault map of the region. Accordingly, two main active fault zones (North Zanjan and Soltanieh faults) can be considered as most hazardous active structures for the city of Zanjan. Whereas, surface traces of other faults (e.g., Sohrein Fault Zone), previously classified as active, are most likely linear erosional features in fluvial terraces due to a regional base level change of the Zanjan River.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-316

Effect of alternative distributions of ground motion variability on results of Probabilistic Seismic Hazard Analysis

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Probabilistic seismic hazard analysis (PSHA) is a regularly applied practice that precedes the construction of important engineering structures. The Cornell-McGuire procedure is the most frequently applied method of PSHA. This study examines the fundamental assumption of the Cornell-McGuire procedure for PSHA, namely, the log-normal distribution of the residuals of the ground motion parameters. Although the assumption of log-normality is standard, it has not been rigorously tested. Moreover, the application of the unbounded log-normal distribution for the calculation of the hazard curves results in non-zero probabilities of the exceedance of physically unrealistic amplitudes of ground motion parameters. In this study, the distribution of the residuals of the logarithm of peak ground acceleration is investigated, using the database of the Strong-motion Seismograph Networks of Japan and several ground motion prediction equations developed for Japan. The distribution of residuals is modelled by a number of probability distributions, and the one parametric law that approximates the distribution most precisely is chosen by the statistical criteria. The results of the analysis show that the most accurate approximation is achieved with the generalized extreme value distribution for a central part of a distribution and the generalized Pareto distribution for its upper tail. The effect of replacing a log-normal distribution in the main equation of the Cornell-McGuire method is demonstrated by the calculation of hazard curves for a simple hypothetical example. These hazard curves differ significantly from one another, especially at low annual exceedance probabilities.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-317

Monte Carlo simulation for decision making in statistical estimation of maximum regional earthquake magnitude

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Maximum regional earthquake magnitude is an important input parameter for seismic hazard analysis. Several statistical methods for estimation of this parameter were developed in the field of seismology. This study examines the properties of some of the methods for estimation of maximum magnitude by using the Monte Carlo simulation technique. Methods are tested with respect to size of the synthesized samples, number of synthesized samples and parameter b of the underlying Gutenberg-Richter distribution. The results of the analysis allow us to conclude about which of the methods is the most stable with respect to the number of the observed magnitudes in the instrumental catalogue, and what amount of observations could be sufficient for obtaining reasonably robust and unbiased estimations of the maximum regional magnitude.

IASPEI (Seismology, Geophysics)

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S07p-318

Subsurface structure and tectonic evolution of concealed active fault in the southern part of Sendai plain, northeast Japan

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Strong Pliocene-Quaternary contraction has occurred mainly in the back-arc side of Northeast Japan (NEJ). On the other hand, week deformation has propagated eastward beneath the forearc. In the forearc side of NEJ, the Western Boundary fault zone of the Kitakami lowland, Nagamachi-Rifu active fault, Futaba active fault, and submarine active faults in the Sendai Bay are located as well known active faults, which contribute to a part of NEJ's horizontal shortening. Although the contraction of forearc side is week, the risk of earthquake disaster along the forearc side is larger than that along the back-arc side, because the forearc side of NEJ embraces a large population. Our study provides a strong constraint for the risk assessment of urban area along the forearc side.

Although, our survey area is located on a junction of Nagamachi-Rifu fault with Futaba fault, the relationship of these two active faults was not so clear. To reveal the subsurface structure beneath the Sendai Plain, we carried out 5.3-km-long seismic reflection survey and gravity survey in 2013. Depth converted seismic profile shows that Pre-Tertiary granite rocks and Neogene-Quaternary sediments are folded and dislocated in conjunction with concealed active faulting beneath the Sendai Plain. Bouguer gravity along seismic line also supports these subsurface structures. The concealed fault seems to be extended toward north, and continues to the eastern foot of Medeshima Hills. To reveal the extension of the concealed active fault, we carried out another gravity survey around the Medeshima Hills in 2014. The bouguer gravity of 2014 survey shows that the concealed active fault terminated at the north of Medeshima Hills.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-319

Seismic hazard assessment of the major pipeline "Yakutia-Khabarovsk", Russia

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During last years Russia actively develops regions in Siberia and Far East. In particular, a number of oil and gas pipelines are designed and constructed in these regions, which necessarily requires the refining of seismic hazard assessment of these territories. The presentation describes seismic hazard study of the major pipeline “Yakutia-Khabarovsk” with the use of probabilistic approach. The goal of the study was to estimate ground motion parameters in terms of peak ground accelerations and seismic intensities that will not be exceeded with the 10% probability during 1, 100, and 500 years and on this basis to make the choice between two alternative variants of the pipeline location. The uniqueness of the study was determined by the object itself whose length exceeded 2500 km and therefore various parts of the route are related with very different seismic conditions from rather seismically active to relatively quiet.
In frames of the study, seismological observations were organized by the temporary network of the Institute of Physics of the Earth, RAS (46 stations, 6 months). Occasionally the network recorded the earthquake near Skovorodino with Mw=6.0 being close to Mmax expected for this region. In the whole, the compiled earthquake database contains more than 4000 events; 8 historical earthquakes were critically revised. On the basis of seismological analysis and seismotectonic observations the source zones model was developed (32 zones, Mmax from 4.5 to 7.5) and employed in hazard calculations. At the last stage, according to the Russian practice of hazard assessment, the results were corrected for site effects.
The work was partly supported by ZAO “SPF “DIEM” and by the Russian Foundation for Basic Research, project no. 14-05-00258.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-320

Probabilistic Seismic Hazard Assessment at the Northwestern Part of Egypt

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Earthquake hazard assessment has a direct social impact in describing levels of ground motions to be expected in a given region for the future. The pre-existing knowledge of the seismic activity level, seismotectonics and fault behavior in a certain region represent input parameters in seismic hazard assessment. Probabilistic seismic hazard assessment (PSHA) at the northwestern part of Egypt is studied in the frame of logic tree. In the current study, Three seimotectonic models are used. The maximum expected earthquake for each seismic zone was determined and the modified Gutenberg-Richter model was adopted for calculations of recurrence parameters. Ground-motion Prediction Equations (GMPEs) which developed based upon seismic data obtained from the active tectonic environments similar to those in and surrounding the studied area were weighted and used for estimating of the horizontal ground accelerations. Consequently, Hazard maps at bedrock sites are produced for peak ground acceleration (PGA) , as well as 5 % damped spectral acceleration (SA) values at periods of 0.1, 0.2, 0.3, 1.0 , 2.0 and 3.0 sec for return periods of 72, 475 and 2475 years. The Unfied response spectra of Alexandria and Marsa Matruh cities is Produced. Then, the hazard curves were deaggregated to determine the sources that contribute at hazard level of 10, % probability of exceedance in 50 years.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-321

Key aspects of a risk-targeted earthquake source model for South-East Asia

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The last decade has tragically shown the social and economic vulnerability of countries in South-East Asia to earthquake hazard and risk. While many disaster mitigation programs and initiatives to improve societal earthquake resilience are under way with the focus on saving lives and livelihoods, the risk management sector is additionally challenged to develop appropriate models to cope with the economic consequences.

We present the source model component suitable for a South-East Asia earthquake risk model covering Indonesia, Malaysia, the Philippines and Indochina countries. The source model component builds upon established and refined used modelling approaches to derive 1) background seismicity, i.e. earthquakes not occurring on mapped fault structures, 2) seismic activity from geologic and geodetic data on crustal faults and 3) activity on the subduction zones. We provide insight and solutions to the complexity of aggregating appropriate data sets for a pan-regional model and analyse uncertainties and sensitivities in the various model-building steps. We illustrate our compilation of an earthquake catalogue accounting for the various pros and cons of those available from global and local agencies and considering published magnitude conversion relationships from the various magnitude types to moment magnitude that have immediate consequences for the determination of earthquake rates.

For this first earthquake rate model we showcase evaluation procedures incorporated in the model building process and highlight model characteristics that distinguish a risk model from a hazard model.

IASPEI (Seismology, Geophysics)

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S07p-322

Coseismic ruptured fault segment and unruptured segment during the Rikuu earthquake (M=7.2), northeast Japan: Subsurface structures revealed by seismic-reflection profiling

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The 1896 Rikuu earthquake (M = 7.2) struck the Yokote basin and adjacent areas in northeast Japan. Although total length of the eastern margin fault zone of the Yokote basin is 56 km, the earthquake caused only 26-km-long surface rupture along the northern segment of the fault zone. The southern 30-km-long segment did not rupture during the earthquake. We investigated subsurface structures of the fault zone for assessment of activity of each active fault segment. Previous researches of the subsurface structure of the 1896 coseismic ruptured northern segment showed an emergent frontal thrust forward branching from a thrust located at boundary between the basin and mountainous area. Crustal shortening during the past 2–3 million years across the northern segment based on the subsurface structure in the past researches is about 2–3 km. Since there were few researches of subsurface structure across the 1896 unruptured southern segment, seismic reflection profiling was conducted across the southern segment in this study. As a result of the seismic survey, a blind frontal thrust branching from the boundary thrust and a fault-propagation fold of hanging wall of the blind thrust were detected. The southern subsurface structure is entirely different from northern one regarding the frontal thrust. Quaternary crustal shortening calculated by cross-section balancing across the southern segment was slightly larger than 1.3 km. These results have suggested that a slip rate of the southern segment during the Quaternary is very smaller than that of the northern segment and recurrence interval on the southern segment is very longer than that of the northern segment.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-323

Crossing the border again: Assessing the differences between Canada's 2015 and the United States' 2014 seismic hazard maps

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The Geological Survey of Canada's new suite of seismic hazard maps will form the basis of seismic design codes in the year 2015 edition of the National Building Code of Canada (NBCC). The United States Geological Survey (USGS) has released a similar set of maps in 2014 covering the conterminous United States for the National Earthquake Hazards Reduction Program (NEHRP). The 2015 NBCC maps now adopt a fully probabilistic model that provides mean hazard values consistent with the approach used by the USGS. This provides an improved basis for comparing the two national models. Differences along the border between Canada's 2015 and the 2007 Alaska maps are also investigated. Correcting for differences in the reference site condition [class C (Vs30 = 450 m/s) in Canada and the B/C boundary (760 m/s) in the United States], there is general agreement in the pattern of hazard and relative hazard levels, as shown by comparing values between Canadian and appropriate U.S. cities and examining border-region maps. However, hazard contours do not necessarily match across the border. Differences in the definition of source zones, choice of ground motion prediction equations, and incorporating Cascadia subduction earthquakes all contribute to these cross-border differences.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-324

Statistical analysis of the seismic sources from the Eastern part of Romania and Black Sea for probabilistic seismic hazard assessment

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The seismic zonation of the Eastern part of Romania and the Black Sea Area was obtained using the distribution map of earthquakes and the map of the zones with active tectonics. There were established in this way fourteen crustal and one intermediate seismic sources: Vrancea intermediate (VRI), Vrancea normal (VN), Barlad Depression (BD), Predobrogean Depression (PD), Intramoesian Fault (IMF), North Dobrogea (BS1), Central Dobrogea (BS2) Shabla (BS3), Istanbul (BS4), North Anatolian Fault (BS5), Georgia (BS6), Novorossjsk (BS7), Crimeea (BS8), West Black Sea (BS9) and Mid Black Sea (BS10).

In this study we have used the most reliable and homogeneous seismicity dataset at the European scale, covering historical and modern instrumental seismicity for the Eastern part of Romania and the Black Sea Area. The catalogue was obtained as a compilation of 4 existing catalogues: ANSS-Advanced National Seismic System-USA, NEIC - National Earthquake Information Centre, World Data for Seismology Denver-USA, ISC-International Seismological Centre-UK and INCDFP – Romplus, Romania.

For each source we have compiled all the requested parameters for a probabilistic hazard assessment: geographical distribution, specific depth, magnitudes and intensities, the activity rate, Gutenberg Richter, Gumbel I and III distributions parameters, maximum possible and most probable magnitudes and their return periods.

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IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-325

Observations on intraplate seismicity in Central Fennoscandia

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Central Fennoscandian is situated in a seismically quiet intraplate setting in northern Europe. Intraplate seismicity has been attributed to ridge-push from the North Mid-Atlantic Ridge, GIA rebound stresses and to local GPE differences associated with compositional differences and crustal thickness variations. An up-to-date estimate of the intraplate seismicity in the central part of Fennoscandian and its sources is needed in seismic hazard estimates of nuclear power plant sites and thus a seismotectonic study has been undertaken.

Based on a subset of the most recent earthquake data,most of the earthquakes (80%) occur in the upper crust, a minority (19%) in the middle crust and only a few in the lower crust (1%). The seismogenic layer is less than 30 km thick and comprises upper and middle crust. The seismically active areas are located in areas where the crust is <50 km thick. Where the crustal thickness gradient trends NE–SW, e.g. along the faulted western margin of the Gulf of Bothnian and along the Auho-Kandalaksha fault zone in Kuusamo, the gradient seems to be associated with a zone of increased seismicity.

Pre-existing deformation zones that are optimally oriented in the present stress field can potentially be reactivated. The deformation zones were analysed for their length and azimuth and they were assigned a potential reactivation type (reverse, normal or strike slip) based solely on their azimuth. In the seismically most active areas, the deformation zones and PGF's appear to be mostly oriented optimally for reverse or strike slip faulting. There is, however, no clear evidence that GIA rebound stress is the main source for triggering seismicity today.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-326

Empirical ground motion characterization for Fennoscandia; GMPE's and spatial distribution

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The Fennoscandian Shield is a seismically quiet area with a scarcity of strong earthquakes and, consequently, an area lacking strong motion data. This lack of empirical strong motion data and the subsequent lack of advanced stochastic and theoretical models of seismic response limit the ground motion prediction equation (GMPE) development for the region. In order to create GMPEs targeted for the Fennoscandian Shield, we take advantage of the comparatively large ground motion database and use a more direct empirical approach . We present GMPEs, which were created by fitting the empirical ground motion data derived from 2239 earthquakes recorded at 88 seismic stations to an existing attenuation equations. The first model relies on an existing predetermined GMPE. The coefficients of the model were fitted to our regional data set by using a non-linear least-squares regression. The second model is a referenced empirical model which relies on modifying the ground motion prediction produced by an existing GMPE by multiplying it with a function of certain seismological parameters. Within the magnitude-distance range of the data set, the resulting equations model the peak ground accelerations and spectral accelerations reasonably well. Residuals of the ground-motion prediction display no clear trend with regards to magnitude or distance. We assess the limits of usability of the GMPEs by applying them to an independent regional earthquake and to various events that have occurred in a similar stable continental area. Another view of attenuation is obtained by utilizing ground displacement values from regional bulletin. This database is larger and it allows to study regional lateral differences in attenuation of seismic waves.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-327

Seismic hazard maps for the Maltese archipelago (Central Mediterranean)

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In the present study we attempt to construct seismic hazard model and produce probabilistic seismic-hazard assessments for the Maltese Islands in terms of Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) at different periods within the archipelago boundaries. So far very few investigations have been carried out on seismicity around the Maltese islands and no maps of seismic hazard for the archipelago are available. Seismic hazard has been computed using the two earthquake source models relying on different assumptions and providing full description of earthquake activity. The first one is the zonation model: seismotectonic and geological data are used coupled with earthquake catalogues to identify seismogenic zones within which earthquakes occur at certain rates. In this study we used several seismogenic zones and include in computation few seismogenic area close to the Maltese islands never considered before. The second one is the spatially smoothed seismicity approach based on the historical and instrumental seismicity generalized using exponential magnitude distributions with regionally determined b-values. It does not take into account any geological and tectonic observations. In order to determine the ground motion parameters related to a specified probability of exceedance, the earthquake source models are combined with ground motion prediction equations (GMPEs). The ground-shaking hazard calculated based on the two source models and appropriate GMPEs through the logic tree approach for a 10% exceedance probability in 50 years for PGA shows values ranging between 0.09-0.18g.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-328

Identification of earthquake-prone areas in some intraplate regions

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Most of seismic intraplate regions are characterized by rare earthquakes, which make difficult employing the probabilistic approach for seismic hazard estimation. In this work we suggest a phenomenological approach based on pattern recognition for identifying seismogenic structures within two intraplate regions. We study the Massif Central located within the West-European platform and the Gujarat area situated at the edge of the Indian shield. The methodology used is based on the idea that earthquakes nucleate at nodes, specific structures forming around fault intersections. Morphostructural zoning method (MZ) was used to identify nodes in both regions. MZ delineates a hierarchical system of blocks with their boundaries, morphostructural lineaments. The intersections of lineaments are viewed as nodes. The pattern recognition technique was employed to identify the seismogenic nodes on the base of geomorphic, geological, and gravity parameters describing nodes. As a result, seismogenic nodes capable of earthquakes with I ≥ VI have been defined in the Massif Central, while in the Gujarat area we have recognized nodes prone to M ³ 5.0 earthquakes We also found the characteristic geological-geophysical features that discriminate seismogenic nodes from non-seismogenic ones. The work provides the methodology and the specific input for seismic hazard assessment in different intraplate regions of the world.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-329

Sensitivity analysis for the quantitative assessment of the source zone model in a low-to-moderate seismicity environment

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One of the most controversial aspects of probabilistic seismic hazard assessment (PSHA) is the definition of the source zone model. Due to the unclear relationship between seismotectonic structures and observed seismicity, the delineation of source geometry for PSHA is characterized by a lack of objectivity and often relies on expert judgement. Furthermore, the limited observed seismicity in light of longer tectonic cycle explains the large uncertainties associated with the recurrence statistics and the source parameters.

In this context, it is crucial to find a procedure to quantify the accuracy and uniqueness of the source model to objectively assess its robustness and reliability. This means: 1) to quantify the uncertainty of the entire source model; and 2) to evaluate how much each input parameter (e.g. geometry of the source zones, recurrence statistics, maximum magnitude, rupture geometry, etc.) contributes to the uncertainty of the output, i.e. the seismic source zone model. Sensitivity analysis, that is an exploration of the multi-dimensional input space, provides a framework for understanding the second task.

In this work we apply the sensitivity analysis to the case study of the British Isles, an intraplate region with low-to-moderate seismicity. Specifically, we compare the source zone model of Musson & Sargeant (2007) with that produced in the SHARE project (Giardini et al., 2013). Musson & Winter (2012) demonstrated that some source zone models are incompatible with observed seismicity using statistical techniques. Here, we find that a source zone model explaining observed seismicity in low-to-moderate seismicity areas is not unique. This means that we cannot reject any of the analysed source zone models because they both reproduce the observed seismicity.

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S07p - S07 Seismic Hazard and Risk

S07p-330

Earthquake loss estimation in the Gyeongju area, southeastern Korea, using a site classification map

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Korean historic and instrumental earthquake catalog were examined in detail to identify areas where a high probability of large earthquakes was indicated. We particularly considered southeastern Korea, where the largest historic earthquake was reported, and small- to moderate-sized earthquakes have frequently occurred during the modern period of instrument observations. The Gyeongju area was chosen after a careful review. Because the extent of ground shaking is strongly influenced by local site conditions, a site classification map of the study area was prepared to provide a realistic simulation of estimated earthquake losses. We then estimated losses due to a magnitude 6.7 earthquake scenario in the Gyeongju area by applying the site classification map. The results indicated large spatial variations in damage estimates in the study area. As the epicenter of the scenario earthquake, the Gyeongju area was predicted to experience significant damage. Despite the large distance from the epicenter, the results indicated that Pohang Nam-gu was expected to experience levels of damage comparable to those in the Gyeongju area. Comparisons of results with and without the use of the site classification map indicated that the large estimated losses were caused mainly by the soft soil conditions that occur widely in the area.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-331

Repeating microseismicity in the Seoul metropolitan area, Korea, and its implications for seismic risk

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An ML 3.0 earthquake occurred in the Seoul metropolitan area (SMA), Korea, on 9 February 2010. The unexpected shaking attracted much attention and raised concerns about the seismic hazards and risks in the SMA, where only a few minor earthquakes had been reported and which was regarded as an area safe from any earthquake hazard. The SMA has a population of 25.6 million and is one of the largest metropolitan areas in the world. We noticed a cluster of closely spaced earthquakes by carefully reviewing continuous seismic record. Although there are historic documents reporting instances of strong shaking and related damage, this is the first time that a clustered seismicity from the instrumental records has been reported. The focal mechanism solution for the earthquake was consistent with the linear trend of precisely determined earthquake locations. It also coincide with the unnamed fault trace appeared in the geological map of Korea. The reliable focal depth is also obtained by the earthquake relocation with P and S arrival times and the sPL depth phase, which shows consistent focal depth of 11~13 km. A shakemap for a scenario earthquake with magnitude 6.5 and focal depth 12 km implies that the SMA will be exposed to serious risk because of its large population and the high vulnerability of its buildings. Although the instrumentally recorded

earthquakes discussed in this article cannot be classified as major events, they should not be discounted as insignificant. Considering the low seismicity and long recurrence interval of damaging earthquakes, extensive efforts to monitor the microseismicity are definitely required to obtain a comprehensive picture of the seismicity pattern of the SMA.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-332

This is my abstract title: "Seismic hazard assessment of territory of Kyrgyz Republic"

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Kyrgyzstan, which is located in a zone of collision between the Eurasian and Indo-Australian lithosphere plates, is prone to large earthquakes as shown by its historical seismicity. In particular, between the end of 19th century and the beginning of the 20th one, several destructive earthquakes struck Kyrgyzstan, such as the Belovodskoe earthquake of August 3, 1885 (maximum intensity IX), that struck the city of Kara-Balty, just west of Bishkek (Bishkek developed as a city within the 20th century), and the Ms=8.3 Kemin earthquake of January 3, 1911. This earthquake killed several hundreds of people and had a strong impact on environment, triggering several mudflows and landslides (Abdrakhmatov et al., 2003). Recently, an earthquake of magnitude Ms=7.3 struck on 19 August, 1992 the western part of the Suusamyr valley, in the north Tien Shan region of Kyrgyzstan. Finally, on October 5, 2008, a magnitude 7.0 occurred along the border triangle between Kyrgyzstan - Tajikistan - China. This earthquake caused the loss of 75 lives, confirming the urgency of developing international program for earthquake risk mitigation in Kyrgyzstan.

The occurrence of close and large earthquakes makes the Kyrgyzstan the region with one of the highest seismic hazard in the world (Zhang, 1999). Probabilistic seismic hazard maps at regional scale have been recently computed for Kyrgyzstan (Abdrakhmatov et al., 2003), confirming the very high hazard of the region. After this investigation at least three more studies on seismic hazard of named territory were carried out (Erdic et.,al., 2005, Parolai et., 2012, Lindholm at.,al., 2013) . The comparison between these studies is presented.

IASPEI (Seismology, Geophysics)

S07p - S07 Seismic Hazard and Risk

S07p-333

The use of probabilistic fault displacement methods in ground displacement and tsunami hazard

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Surface displacement hazard analysis due to slip on a fault is commonly used in circumstances where a project site crosses an active fault but also in the context of a probabilistic tsunami hazard analysis. In the former case, this analysis used to be limited to offset along the main fault, but more recently models have developed that also consider displacement hazard on secondary structures. Recently, with the advent of numerical approaches to tsunami hazard analysis, it has become desirable to use a probabilistic surface deformation model as input to tsunami hazard calculations. For complex fault ruptures or recurrence models, or buried faults, the probabilistic analysis needs to be carried out all the way to the ground deformation. We will present examples of applications of the PFDHA method, both in its strictly empirical form in engineering applications and in a numerical form, for tsunami hazard purposes.We are also developing a hybrid method for computing full probabilistic ground deformation through a combination probabilistic fault displacement and numerical computation of the resulting ground deformation. Using a Green's function approach, by pre-computing ground deformation fields for a set of sufficiently small elementary subfaults, we can rapidly compute the co-seismic ground deformation for any earthquake on the fault allowing for a comprehensive source integration. Aleatory uncertainties from the probabilistic fault displacement can be carried over to the displacement field because linearity of the system and epistemic uncertainties are included in the same way as in traditional PSHA. The ground deformation parameter can be chosen as appropriate for the problem at hand, be it fault displacement, uplift, subsidence, or strain in arbitrary directions.

IASPEI (Seismology, Geophysics)

S08a - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-1489

Quantitative texture analysis and seismic properties of mantle peridotites (Balmuccia, Italy)

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Balmuccia massif (Ivrea zone, Italy) offers one of the large exposure of sub-continental mantle rocks at the Earth's surface. Emphasis of the study is placed on the relating mineral crystallographic preferred orientations (CPO) to ultramafic rock compressional (Vp) wave velocities and their anisotropies. The ultramafic peridotites from the Balmuccia massif are mainly composed of olivine and ortho- and clinopyroxenes with varying volume fractions. CPO's measurements were performed at the texture diffractometer SKAT at Dubna, Russia. Using the orientation distribution function (ODF) as a parameter characterizing the CPO of the constituent minerals, the seismic properties (3D velocity distribution of P-waves) of bulk samples were calculated from the corresponding properties of major minerals. It was shown that the elastic anisotropy of peridotites strongly depends on olivine crystallographic textures. The complete 3D P-wave distributions at confining pressures ranging from 0.1 to 400 MPa were measured at the Institute of Geology AS CR (Prague, Czech Republic). The texture-derived P-wave velocity distributions reflect the experimentally determined bulk rock anisotropy quite well. Known CPO patterns and P-wave velocity distributions deliver significant information on deformation processes during mantle emplaced into the crust.

IASPEI (Seismology, Geophysics)

S08a - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-2684

Upper mantle structure of the transition between Alps and Apennines revealed by shear wave splitting from the CIFALPS project

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The structure of the upper mantle beneath the Alps and Apennines has been studied repeatedly in the past. Several studies focused on the seismic anisotropic properties to delineate the strain distribution in the litho-asthenosphere. However, Northern Apennines, Alps and surrounding regions are often studied separately. A joint interpretation of the Alps-Apennines transition zone is still lacking. In this perspective, the China-Italy-France Alps seismic survey (CIFALPS) provided an improved image of the crust and upper mantle beneath the southwestern Alps and the transition to the Apennines. Here we show the SKS shear wave splitting results obtained from the analysis of teleseismic data recorded by 55 temporary seismic stations along the CIFALPS profile and by some other permanent stations. The strain-induced lattice preferred orientation of olivine minerals within the upper mantle, expressed by the analysis, confirms the NW trending fast polarization directions parallel to the strike of the orogen, in good agreement with the results of previous studies all along the Alpine chain. On the contrary, in the Po Plain, new shear wave splitting measurements show a scattered distribution; the coexistence of both NNE-SSW and E-W directions provides new insights on upper mantle deformation in the complex transition zone between the Alpine and Apenninic subductions. An interpretation drawn using geological records is under construction.

IASPEI (Seismology, Geophysics)

S08a - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-3082

The influence of water on seismic wave attenuation in the upper mantle

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A fine-grained synthetic olivine (Fo90) polycrystal, doped with ~0.04 wt% TiO_2, has been prepared with ~70 wt ppm H_2O accommodated in the Ti-clinohumite defect typical of natural olivines from the Earth's generally water-undersaturated upper mantle (Berry et al., Geology, 2005). A precision-ground cylindrical specimen of this material, sleeved in Pt tubing within a mild-steel jacket, was tested in torsional forced oscillation at seismic frequencies (mHz-Hz) and temperatures to 1200C, under 200 MPa confining pressure. The shear modulus was observed to decrease systematically with increasing oscillation period and temperature, accompanied by monotonically increasing dissipation - observations characteristic of absorption band or high-temperature-background behaviour. Comparison with the model of Jackson and Faul (Phys. Earth Planet. Interiors, 2010) for a suite of essentially anhydrous olivine polycrystals, evaluated at the 50 micron grain size of the hydrous titaniferous olivine specimen, shows that the latter is vastly more dissipative than its anhydrous equivalent (by an order of magnitude at 1200C) and correspondingly lower in shear modulus. The new data are strikingly similar to those of Aizawa et al. (J. Petrol., 2007) for a specimen of Anita Bay dunite mylonite encapsulated in Pt and subject to in situ dehydration of hydrous accessory phases to produce ~2 vol % of an aqueous fluid phase. At face value, the new results suggest a very strong influence of water on seismic wave attenuation – even under the water-undersaturated conditions expected to prevail in the Earth's upper mantle. Follow-up experiments are underway to better characterise the mechanical behaviour of the enclosing Pt sleeve, and of anhydrous titaniferous olivine of comparable grain size.

IASPEI (Seismology, Geophysics)

S08a - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-4617

Mechanisms and geologic significance of the mid-lithosphere discontinuity in the continent

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Recent high-resolution seismological studies have revealed a puzzling structure of the stable continents: a marked velocity drop at a mid-lithosphere depth (the mid-lithosphere discontinuity). This discontinuity has been attributed to later modifications to continental lithosphere leading to changes in composition, anisotropy and/or partial melting implying that "stable" continents have undergone major modifications during their geologic history. We show that these models are difficult to reconcile with the nearly global presence of this discontinuity and with the approximately depth-independent ages of mantle rocks in most old continents. We propose that elastically-accommodated grain-boundary sliding is a likely cause of most mid-lithosphere discontinuities. This process occurs in any polycrystalline materials at a modest temperature and results in a substantial reduction in seismic velocity without major changes in composition and long-term rheological properties. Therefore this model is consistent with a concept of stable old continental lithosphere. However, significant variations in the depth of the mid-lithosphere discontinuity occur that can be attributed to the regional variations in temperature and/or water content. Both of these factors reflect the geologic history of a continent and affect its rheological properties. Therefore, the mid-lithosphere discontinuity carries a clue to the dynamics and evolution of the continents.

IASPEI (Seismology, Geophysics)

S08a - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-5318

High-resolution teleseismic tomography study of the upper mantle structures below POLENET/LAPNET array in northern Fennoscandian Shield

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POLENET/LAPNET project was a passive seismic array experiment in northern Fennoscandia during the International Polar Year 2007-2009 with seismic stations recording in northern Finland, Sweden, Norway and Russia. The study area extended between 18-31 degrees E and 64-70 degrees N. The tectonic history of the area is dominated by two Early Proterozoic orogenies: Lapland-Kola orogeny, during which two provinces of Archaean Karelian craton collided, and Lapland-Savo orogeny, durin which Karelian Craton and Norbotten Craton collided.

One of the major targets of POLENET/LAPNET array was to obtain a 3D seismic model of the upper mantle in the northern part of the Fennoscandian shield. To reach this aim we use a high-resolution teleseismic traveltime tomography. 3167 arrivals of P-waves from 97 teleseismic events with epicentral distances of 30-90 degrees were manually picked, the southern part of the data set was increased with 360 P-wave arrivals from earlier and partially overlapping SVEKALAPKO project, and inverted using TELINV code.

As the crustal thickness in the study area varies from 40 km to almost 60 km, the traveltimes of P-waves were corrected for the effect of the crust using the crustal velocity model compiled from previous results of controlled-source seismic profiling, P-wave receiver function studies, and seismic noise tomography in the area. The resolution analysis demonstrated that resolution of POLENET/LAPNET data is reasonably good between depths of 70 km and 360 km. The main feature of the inversion results is slow velocity anomalies of about -2.5% below the contacts of all three cratonic components in the area. The anomalies extend from below the crust down to 160 – 200 km in depth.

IASPEI (Seismology, Geophysics)

S08b - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-1480

The distribution of lithospheric heterogeneity and the nature of the lithosphere-asthenosphere transition.

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A variety of lines of evidence suggest the presence of fine-scale heterogeneity in the mantle component of the lithosphere, both oceanic and continental. These include the properties of high-frequency guided waves from both natural and man-made sources and receiver function studies in both observational studies and numerical simulations.
In the oceanic domain a style of heterogeneity with much longer horizontal correlation length than vertical appears to be appropriate to both the lithosphere and asthenosphere, with differing levels of wavespeed variation. The transition from lithosphere to asthenosphere can be abrupt and reflect the presence of melt in the asthenosphere, possibly as a change of hydration state.
In the continents, the ancient cratonic areas show very high seismic wavespeeds and normally low seismic attenuation. Propagation of high-frequency energy to long distances is again consistent with elongate stochastic heterogeneity, but with some depth variation. Mid-cratonic discontinuities may well arise from a change in heterogeneity state, with an extended transition into the asthenosphere below with little in the way of a distinctive marker. As a result of the very high wavespeeds near 100 km depth the lower part of the lithosphere, though seismically fast, can lie in a pronounced low velocity zone. Across Australia the character of the lithosphere to asthenosphere transition appears to a link to the age of the lithosphere that involves a modification of the heterogeneity distribution in depth.

IASPEI (Seismology, Geophysics)

S08b - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-1764

LAB - transition between fossil and present-day flow-related velocity anisotropy

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Fundamental difference in origin and orientation of seismic anisotropy in the mantle lithosphere and in the sub-lithospheric mantle has led us to developing an original approach of LAB modelling. We define the LAB as a boundary between a fossil anisotropy in the lithospheric mantle and an underlying seismic anisotropy related to present-day flow in the asthenosphere. We present (1) a uniform updated model of the European LAB calculated from P-wave travel times collected during several regional passive experiments (Plomerova and Babuska, 2010), and (2) a global model (Plomerova et al., 2002) calculated from depth-dependences of polarization and radial anisotropy of surface waves. In model (1) we transform lateral variations of static terms of relative residuals into a LAB relief according to an empirically derived residual-depth relation with a gradient of 9.4 km/0.1s The high velocity contrast across the LAB (δv_P ~ 0.6 km/s), resulting from the empirical gradient, can be explained by considering generally inclined high-velocity directions in the mantle lithosphere and sub-horizontal high-velocity directions in the asthenosphere. The global model (2) shows the LAB at depths of 200-250 km in Precambrian shields and platforms, around 100 km in Phanerozoic continental regions and between 40 and 70 km beneath oceans. Lithosphere roots down to ~ 220 km are mapped in model (1) beneath the Western and Eastern Alps, central Fennoscandia and the East European Craton. LAB depth changes at the Trans-European Suture Zone and it is shallower beneath the Phanerozoic Europe with more distinct lateral changes than beneath its Precambrian part. Incorporating seismic anisotropy enables us to construct self-consistent models of the LAB and large-scale fabrics of the lithosphere.

IASPEI (Seismology, Geophysics)

S08b - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-1778

Structure of the LAB and MLD in the northwestern and central United States from USArray S-receiver functions

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We used more than 40,000 S-receiver functions recorded by the USArray project to study the structure of the mantle lithosphere from the Phanerozoic western United States to the cratonic central US. We obtained clear observations of downward velocity reductions below the Moho which are interpreted as lithosphere-asthenosphere boundary (LAB) in the western US and as mid-lithospheric discontinuity (MLD) in the central US. The topography of both discontinuities is very complex.

In two regions, north of Yellowstone and south of the Colorado Plateau, the LAB signal extends from the west coast to approximately the Mid Continental Rift System (MCRS). In these two regions it dips from near 100 km depth at the west coast to near 200 km depth at the MCRS. In between, from Yellowstone to the Colorado Plateau the LAB reaches from the west coast only approximately to the Sevier Thrust Belt where it stops abruptly.

The MLD is observed near 100 km depth in the central US. It extends approximately to the Great Plains in the west with the exception of the same region between Yellowstone and the Colorado Plateau as above. In this region the MLD dips to the west from 100 km depth at the Great Plains to about 200 km depth near the Sevier Thrust Belt. There exists a big break in the lithospheric mantle approximately below the Sevier Thrust Belt. West of it we observe the LAB at 100 km depth. There is no LAB east of the break and instead we observe here the MLD at the unusual depth of about 200 km. The nature of the MLD, which is a global shallow velocity reduction in cratons, is still disputed and so far no models exist for its role in continental collision.

IASPEI (Seismology, Geophysics)

S08b - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-1949

Passive margin volcanism in eastern Australia and the role of the lithosphere-asthenosphere boundary

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In-board of the east coast of Australia, a nearly 4,000 km long passive margin, the Palaeozoic orogens formed along the proto-Pacific margin of East Gondwana exhibit extensive evidence of prolonged intra-plate basaltic volcanism. Although the majority of volcanism occurred in the Cenozoic, activity can be traced back to the mid-Cretaceous. The most recent eruptions are less than 5 ka, and occurred within the Newer Volcanics Province (NVP) in western Victoria. The vast extent of the intra-plate volcanism, and the identification of a number of distinct age-progressive pulses, has given rise to many different models that attempt to explain the origins of this relatively recent phenomenon. In this presentation, we focus on the origins of the NVP, which is characterised by the existence of over 700 eruption points, the oldest of which is about 4.5 Ma. Using a combination of seismic tomography and 3D geodynamic modelling, we show that the source of the NVP is restricted to the upper mantle, and that mantle upwelling triggered by edge driven convection (EDC) along a nearby craton edge is localised and intensified by variations in LAB depth and plate motion induced shear flow. This result ostensibly rules out a plume source for the NVP, but the existence of a nearby hot spot track with an age similar to the origin time of the NVP points to the possibility of fertilisation from a deeper mantle source, which may have enhanced melting. Using our new tomography results, we also show that there is a strong correlation along the eastern margin of Australia between LAB depth and the presence of intra-plate volcanism, with thicker lithosphere appearing to resist or deflect the passage of upwelling material.

IASPEI (Seismology, Geophysics)

S08b - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-2551

Upper mantle structure around the Trans-European Suture Zone obtained from teleseismic tomography

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The presented study is focused on the upper mantle structure and the seismic lithosphere–asthenosphere boundary (LAB) around the Trans-European Suture Zone (TESZ). We used data obtained from the temporary and permanent seismic stations deployed within the study area from Germany and the Czech Republic to Lithuania during the period of the PASsive Seismic Experiment (PASSEQ) 2006–2008. We compiled a dataset of more than 8000 manually picked arrivals of P waves from the teleseismic earthquakes, and used a nonlinear teleseismic tomography algorithm to invert it. As the seismic stations used in this study were sampling both the old East European Craton (EEC) and younger Western Europe, we obtain the results showing very different distribution of the P wave velocity perturbations on both sides of the TESZ. In the eastern part of the study area we observe mostly positive velocity perturbations compared to the reference IASP91 velocity model, while the negative perturbations are characteristic to the western part. We also find that the seismic LAB is more distinct beneath Western Europe than beneath the EEC. The shallowest seismic LAB at about 70 km depth in the study area is observed under the Bohemian Massif, the Sudetes Mountains and the Eger Rift, while under the Variscides the seismic LAB is at about 100 km depth. We do not recognize the seismic LAB beneath the EEC, but beneath Lithuania we find the thickest lithosphere of about 300 km or more. The seismic LAB beneath the TESZ is at intermediate depth between that of the EEC and Western Europe. Moreover, our results imply that the seismic LAB in the northern part of the TESZ is in the shape of a ramp dipping to the NE direction, while in the southern part the LAB is shallower.

IASPEI (Seismology, Geophysics)

S08c - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-2252

The Lithosphere Asthenosphere Boundary (LAB) beneath sedimentary basins

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Depending on their plate-tectonic setting, sedimentary basins are characterized by rather different configurations of the lower crust and the LAB. Using lithosphere-scale, data-constrained structural models of passive margins, intracontinental basins and foreland basins we compare these different configurations of the lower crust and the LAB and address the consequences of the latter on the physical states of these systems. We find that the age-dependent depth of the oceanic LAB of passive continental margins may exert first order influences on the thermal field within the sedimentary basins on the stretched continental crust. Moreover, age-dependence is a key factor also for the continental lithosphere in that Precambrian lithosphere is considerably thicker than Phanerozoic lithosphere. Likewise, the lithosphere thickness changes rapidly across orogen-forland systems. These differences result in specific temperature and density configurations that in turn will affect the isostatic state and the rheological behavior of these settings.

IASPEI (Seismology, Geophysics)

S08c - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-2708

Observation of the lithosphere-asthenosphere boundary below Japan

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The lithosphere-asthenosphere boundary (LAB) remains an enigmatic transition that is not always resolved on seismic images. If there is melt in the asthenosphere, the LAB would constitute a shear-wave impedance contrast that is likely large enough to image from above with shear waves. Japan has a large and well-sampled network of tiltmeter stations to observe possible LAB reflections. Moreover, there is abundant seismicity in the crust to ensure plentiful illumination from above. However, possible LAB reflections are hard to uncover from the responses due to much more energetic direct and scattered surface waves arriving in the same time window. As an alternative, we extract shear-wave reflections by applying seismic interferometry to ScS reverberations. Large magnitude earthquakes nearby Japan generate a clear ScS phase that is observed over the entire island arc. For deep earthquakes, additionally ScS reverberations can be observed from interfaces ranging from the lithosphere to the mantle transition zone. We apply seismic interferometry to a multitude of these ScS arrivals and reverberations. Doing so, the responses are retrieved as if there were shear-wave sources at all tiltmeter stations and zero-offset reflection responses were measured. We further migrate the reflection responses to a reflectivity image. The main features on this image are the topography of the 410 and 660 discontinuities. Furthermore, a negative impedance contrast is observed undulating around 170 km depth. We assess whether this could be the LAB, and if so, how it spatially varies below Japan.

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S08c - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-3244

Heat loss and hydrothermal redistribution through the oceanic lithosphere

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We present the analysis of oceanic heat flow designed to estimate: (1) lithospheric heat loss (29.4 TW) and (2) thermal power redistributed by ventilated hydrothermal circulation in young oceanic crust (8 TW). Conductive heat loss through the oceanic lithosphere has been notoriously difficult to estimate accurately due to the redistribution of heat by ventilation of sea water and hydrothermal circulation through igneous basement. By filtering a new global heat flow database (>60,000 sites) for regions with thick sediment cover (>400 m) and far from seamounts (>60 km)---environmental factors that affect hydrothermal ventilation---we find an increase in heat flow versus crustal age relation as predicted by Lister (1972). Supplementing the youngest ages (<25 Ma) with site specific studies, we show the global heat flow--age data are best-fit by a plate cooling model with a 90 km thick plate, 3.5 W m^{-1} K^{-1} thermal conductivity, and 1364ºC basal temperature. Analysis of the heat flow data excluded from the conductive analysis produces a more robust estimate of the heat redistributed by hydrothermal circulation. The hydrothermally affected data binned by age exhibit a larger hydrothermal signal than previously observed, but once accounting for areas where hydrothermal circulation is likely and non-Gaussian data distributions, we estimate a ~30% reduction in the redistributed global power compared to previous analyses. By designing experiments in regions with variable thickness sediment cover and desired proximity to basement exposures, we can improve our ability to target specific questions regarding the thermal evolution of the Earth and it's lithosphere.

IASPEI (Seismology, Geophysics)

S08c - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-3707

Mapping lithosphere thickness using global heat flow and geotherms

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“Lithosphere” was first defined 100 years ago as the outer layer of the Earth, including the crust and part of the upper mantle, having sufficient strength to support loads such as those imposed by mountains, volcanoes, and major river deltas. The term gained prominence in the plate tectonic revolution of the 1960s when “lithosphere” became synonymous with “plates.” But, whereas the lateral boundaries of plates are well known from seismicity or tectonic activity, the identification of, and depth to, the lithosphere-asthenosphere boundary has been much more elusive. In this paper we revisit and update the analysis of Pollack & Chapman (1976) and Chapman & Pollack (1977) in which they constructed regional geotherms for continental and oceanic regions, identified the base of the lithosphere as the point where the geotherm reaches 0.85 of the mantle melting temperature, and produced a global map of lithosphere thickness based on the regional variation of surface heat flow. The current analysis benefits from four decades of advances in: (1) global heat flow coverage, (2) understanding oceanic heat flow variations, especially the role of hydrothermal convection, (3) measurements of thermophysical properties of rocks at elevated temperatures, (4) a better radiogenic heat generation profile for continents, and (5) tighter constraints on geotherms from xenolith studies. The revised models still lead to a variation of oceanic lithospheric thickness from 7 to 150 km, strongly correlated with crustal age, and continental lithosphere thickness from 65 km in rift provinces to more than 200 km under cratons.

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S08c - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-4170

A brief against the hyphen lithosphere-asthenosphere boundary hypothesis of plate tectonics

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The lithosphere is the mechanically strong boundary layer, comprising crust and uppermost mantle, that lies above a much weaker asthenosphere. A tenet of plate tectonics states that the lithosphere-asthenosphere boundary (LAB) marks the kinematic base of lithospheric plates, which slide over the deeper mantle by large-scale shearing concentrated in the upper part of the asthenosphere. Mantle structure is inconsistent with the LAB hypothesis. Beneath old ocean basins, the LAB is marked by a sharp Gutenberg (G) discontinuity at depths of 50-80 km; beneath stable continents, this transition is seismologically less distinct, but its depth is almost certainly less than 250 km. Vertical correlations of seismic velocities from global and regional tomographic models indicate that, on the lateral scale of plates, the asthenosphere translates coherently with lithosphere, beneath oceans to depths of at least 170 km over the lifetime of most oceanic lithosphere and beneath stable continents to depths of at least 350 km over much longer time spans. The vertical S-wave travel time through the oceanic upper mantle decays almost linearly with the square-root of crustal age out to 200 Ma, consistent with a deep conductive cooling model, although some models show a low-velocity anomaly in the older parts of the Pacific basin, consistent with some convective heat flux. We speculate that plate shear beneath stable continents, and perhaps elsewhere, may be concentrated in weak layer of low S velocities immediately above the 410-km discontinuity. In any case, the vertical scale of plate-coherent horizontal flow appears to exceed that assumed in most models of plate dynamics.

IASPEI (Seismology, Geophysics)

S08d - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-0339

Integrated geophysical study on the deep structure of Bohai Bay region

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The North China Craton is the only place where intensive destruction of thick Archaean lithosphere on earth. It is considered by scientists as “a best example of ancient lithosphere destruction”. Based on the results of two onshore-offshore deep seismic profiles across the Bohai Bay region, earthquake tomography and gravity-magnetic inversion in this region, we find that the lower crust anisotropy and small-scale high velocity zones exist in the region and no large-scale undulance of the Moho, and we propose lithosphere thinning is mainly caused by the upper mantle extension. The result indicates that lateral variation of the Moho interface and the crustal P-wave velocity are affected mostly by the existence of large-scale faults nearby, and lower crust was underplated and transformed by the Moho. There is no geophysical evidence support the “mantle plume” or “delamination” model of the North China Craton destruction in our experiment. Therefor, we suggest that the crustal structure of the region shows “a relatively normal crust and thinned mantle” and instability phenomena that shows P-wave velocity anomalies in the crust may represent a combined effect of North China Craton -Yangtze collision at the early stage and the distal effect of the Pacific plate subduction at the late stage.

IASPEI (Seismology, Geophysics)

S08d - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-3756

Looking at the roots of the highest mountains: The lithospheric structure of the Himalaya-Tibetan orogen from a geophysical-petrological study

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By combining geophysical and petrological information, we investigate the crust and upper mantle of the Himalaya-Tibetan orogen, characterizing the lithosphere from the thermal, compositional and seismological viewpoint. The resulting crust and upper mantle structure is constrained by available data on elevation, Bouguer anomaly, geoid height, surface heat flow and seismic data including tomography models. A new 2D crustal and lithospheric mantle cross-section up to 400 km depth in the western Himalaya-Tibetan region is presented, crossing the Tarim Basin, Tian Shan, and Junggar region. Our results show a Moho depth of ~40 km beneath the Himalayan foreland basin, progressively deepening northeastwards to ~90 km below the Kunlun Shan. Northward, the crust-mantle boundary remains nearly flat at 50-65 km depth. The lithosphere-asthenosphere boundary lies at 260-290 km depth below the Himalaya and Tibetan Plateau, Tian Shan and Altai Range, and it shallows to ~230 km depth below the southern Tarim Basin and to ~170 km below the Junggar region. The modeled lithospheric mantle composition is compatible with a generic lherzolitic mantle-type, slightly changing to a more undepleted composition in the deep lithosphere beneath the Tarim Basin due to metasomatism. The Central Asia Orogenic Belt region (Tian Shan, Junggar region and Altai Range) is characterized by a FeO-MgO-rich mantle, likely related to subduction slab-derived fluids. We apply the same modeling approach to existing lithospheric models in the eastern sector of the Himalaya-Tibetan orogen, and compare the results to understand the connection between the present-day lithospheric features and the geodynamic context of the area.

IASPEI (Seismology, Geophysics)

S08d - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-3764

First observation of the lithosphere-asthenosphere boundary and upper mantle discontinuities at the northeastern Atlantic ocean bottom by receiver functions

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Within the DOCTAR project (Deep OCean Test ARray), we installed an array with twelve ocean bottom stations (OBS) in the deep ocean (4-6 km) 800 km West of the Portuguese coast. The array was located 100 km North of the Gloria Fault which marks the plate boundary between the Eurasian and African plate in the Eastern Mid Atlantic. The OBS recorded ten months of data and were equipped with broad band seismometers.

We employ receiver functions (RF) to have a closer look at the structure of the oceanic lithosphere and mantle. We use move out corrected and stacked RF of all stations to estimate average depth values of the Moho and the lithosphere asthenosphere boundary (LAB). The Moho lies at a depth of 7 km and the LAB at approximately 50 km which fits well to crustal ages of 70 Ma.

On the other hand, the single stations of the array offer the opportunity to image the local sedimentary and lithospheric structure. We present RF profiles to show the local structure of Moho and LAB across the array with an aperture of 75 km. The LAB peak for the single stations varies in time delay (4.4 – 7 s) and appearance. This can be caused by the varying sedimentary coverage within the array (between several hundreds of meters and no coverage at all). Therefore, an important conclusion for OBS RF studies is to take sediments into account if crustal thicknesses and the depth of underlying structures (e.g. LAB) are estimated.

The mantle transition zone shows a larger time difference (+0.6 s) between the 660 and 410 compared to PREM. Furthermore, we demonstrate that the analysis of the P wave polarization on OBS can be used to estimate absolute S velocity profiles, and to construct a 1D velocity model by combination with RF studies. Synthetic RF are useful to further tune this velocity model.

IASPEI (Seismology, Geophysics)

S08d - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-4528

Mid-Lithospheric discontinuity below oceans from seismic surface waves.

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The nature of Lithosphere-Asthenosphere boundary (LAB) is controversial according to different types of observations. Using a massive dataset of surface wave dispersions in a broad frequency range (15-300s), we have developed a 3D anisotropic tomographic model of the upper mantle at the global scale. It is used to derive maps of LAB from the resolved elastic parameters, below oceans according to 3 different proxies which correspond to the base of the lithosphere from the vertically polarized shear velocity variation at depth, the top of the radial anisotropy positive anomaly and from the changes in orientation of the fast axis of azimuthal anisotropy. The LAB depth determinations of the different proxies are basically consistent for each oceanic region. The estimates of the LAB depth based on the shear velocity and azimuthal anisotropy proxies increase from thin (20 km) lithosphere in the ridges to thick (120-130 km) old ocean lithosphere. The radial anisotropy proxy presents a very fast increase of the LAB depth from the ridges, from 50 km to older ocean where it reaches a remarkable age-independent profile (70-80km).

The results present two types of pattern of the age of oceanic lithosphere evolution with the LAB depth. The shear velocity and azimuthal anisotropy proxies show age-dependent profiles in agreement with thermal plate models while the LAB based on radial anisotropy is characterized by a shallower depth, defining a subhorizontal interface with a very small age dependence for all three main oceans (Pacific, Atlantic and Indian). These different patterns raise questions about the nature of the LAB in the oceanic regions, of the formation of oceanic plates, and of the existence of a mid-lithospheric discontinuity within the oceanic lithosphere.

IASPEI (Seismology, Geophysics)

S08d - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-5702

Thermochemical structure of the Hudson bay lithosphere, northern Canada: evidence from multi-observable probabilistic inversion

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The geometry of the Paleoproterozoic Trans-Hudson Orogeny (THO), a Himalayan-style collision coalescing the two largest North American cratonic blocks, is difficult to ascertain from surface geology as much of the structure is concealed beneath the Paleozoic Hudson Bay (HB) intracratonic basin. Seismographs placed around the periphery of the Bay have provided a wealth of data in recent years, facilitating regional-scale studies of lithospheric structure.

To investigate the thermal and compositional structure of the Hudson Bay lithosphere we perform multi-observable probabilistic inversions of Rayleigh wave phase velocities, geoid anomalies, elevation and surface heatflow, yielding a pseudo-3D model of the upper mantle.

Broadly, HB lithosphere is characterised by pervasive low temperatures and high degree of chemical depletion. The thermal lithosphere is >250 km thick, possibly to 300 km in the Bay's centre. The phase-velocity data are best explained by a stratified lithosphere, in which the upper layer is highly-depleted and the lower layer has a more fertile character (though still depleted compared to the average non-cratonic lithosphere). Within the upper layer, a relatively narrow zone of lower depletion is visible across HB and Hudson Strait, coinciding with the inferred location of the THO collision zone. This zone likely preserves the signature of juvenile material trapped between the cratonic cores at the end of the THO collision.

Outstanding issues remain; in some areas beneath the cratons there is evidence from intermediate-period phase-velocities for anomalous mid-lithospheric

structure. Variations in long-period phase velocities also suggest the presence of localised thermal heterogeneities in the sublithospheric mantle and transition zone beneath the region.

IASPEI (Seismology, Geophysics)

S08e - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-0426

Crustal thickness and Poisson's ratio in the junction of the Taihangshan and Yanshan tectonic belts in the North China Craton

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We collected waveforms of worldwide teleseismic events with magnitude greater than 5.5 recorded by 192 seismic stations from the Beijing metropolitan Digital Seismic Network and 4 temporary broadband seismic arrays deployed in the junction of the Taihangshan region and the Yanshan tectonic belt during different periods of 2001-2013. Using the receiver functions of the H-κ and CCP stacking methods, we obtain the crustal thickness and average Poisson’s ratio beneath 134 stations deployed on bedrocks.
The comparison of our results of the H-κ and CCP stacking methods shows that our results are self-consistent and in conformity with the previous studies as well, which means reliable. Comprehensive analyzing the fine crustal constraints distribution information in this study, we concluded that (1) the crustal thickness of our study area gradually decreases from northwest to southeast overall; there is a distinct small scale differentiation on both sides of the NSGLNorth-South Gravity Gradient Lineament and its nearby regions. (2) the spatial distribution of average Poisson’s ratio in this region is quite nonuniform; there is significant difference on both sides of the NSGL, which indicates the crustal material compositions has obvious regional difference. (3) the strong earthquake activitiesare closely related to the spatial differentiation of the Poisson’s ratio and the difference of crustal medium properties and middle-upper crustal structure. (4) the crustal thickness and Poisson’s ratio can be divided into 2 relative aggregated group. Though they decrease linearly with the increase of crustal thickness slowly, they may reflect that those areas experienced distinct process of crustal modification in the tectonic evolution process of the North China Craton.

IASPEI (Seismology, Geophysics)

S08e - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-0495

Crustal velocity structure by receiver functions inversion and travel-times for regional phases under Franz Josef Land Archipelago

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The recent (2011) installation of seismic station Zemlya Franca-Iocifa (ZFI, lat=80.81, lon=47.66) on Alexander Island in the Franz Josef Land Archipelago allows new seismic monitoring of the “continent-ocean” transition zone of the Barents-Kara Sea region. The crustal velocity structure beneath ZFI was determined using P-receiver functions technique. We used original broadband three-component records of 41 teleseismic earthquakes. The resulting P-receiver functions we invert to 1D-velocity model. We modeled the medium under the ZFI station by a set of horizontal layers underlain by a homogeneous half-space. Crustal thickness is 30 km, based on an observed Moho discontinuity with underlying mantle velocities being Vp=8.15 km/s and Vs=4.5 km/s. The model indicates a mid-crustal boundary at a depth of about 17 km with a velocity contrast between the upper (Vp=6.1, Vs=3.6 km/s) and lower (Vp=6.8, Vs=3.9 km/s) layers. In addition, the upper crustal sedimentary layer is about 4 km thick with Vp=4.3 km/s and Vs=2.36 km/s. This 1D-velocity model allowed us to calculate travel-times for regional phases – NOES (North of Eurasian shelf) for better location of earthquakes in the area of spreading ridges of the Euro-Arctic Region: Gakkel and Knipovich ridges, areas near Franz Josef Land Archipelago. NOES travel-time is effective at routine processing of records of seismic stations ZFI, SPA0, KBS, HSPB, BJO1, HOPEN and other arctic seismic stations.

IASPEI (Seismology, Geophysics)

S08e - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-2790

Toward a uniform measure of crustal thickness

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The Moho was discovered by seismic refraction and is characterized by a significant, downward increase in P-wave speeds. While there is a consensus in its interpretation as the transition between the crust and the upper mantle, the Moho is spatially variable and by no means always a simple interface. Also, it can be difficult to compare results from different methods, as basic geometry and nature of wave propagation, and frequency content of signals vary considerably.

Here we propose Virtual Deep Seismic Sounding (VDSS) as a potential method for providing a uniform measure of crustal thickness. VDSS uses SV-to-P conversion off the free surface as a virtual source to generate P-wave reflection off the Moho (“ SsPmp”). At distances less than about 55°, the reflection off the Moho is post-critical, resulting in large amplitudes. Thus, high-quality data from a single earthquake, with no stacking and little filtering, yield a clear signal from the Moho.

To minimize source-side scattering, the sources were limited to deep earthquakes. Lately, using particle motions, we overcame this limitation by separating P- and S-wave portions of the signal and remove source-side scattering by deconvolution. This advance paves the way for using the large move-out of SsPmp to minimize the trade-off between crustal thickness and the average speed of P-waves in the crust.

VDSS has been successfully applied to array data over apertures of more than 1,000 km and in places where the crustal thickness reaches 75 km. Simplicity of VDSS, deep-penetrating power of earthquakes, low cost and minimal environmental impact attest to the potential of this robust method for providing a uniform measure of crustal thickness when details of the Moho are not the primary concern.

IASPEI (Seismology, Geophysics)

S08e - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-4048

Mapping the Hales discontinuity in southwestern Spain

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During the last 15 years, the IBERSEIS and ALCUDIA controlled source experiments have acquired vertical incidence and wide angle seismic reflection data in southwest Spain. Apart from providing detailed information of the crust, these datasets have also imaged a conspicuous sub-crustal reflector. First identified on the IBERSEIS wide-angle reflection dataset, this interface seemed to feature a positive seismic impedance contrast. A boundary located between 62-71 km depth, with a Vp increase from 8.2 km/s to 8.3 km/s allowed us to model clear wide angle reflections found at 180 km offsets. The fact that this reflector was not identified in the coincident vertical incidence dataset led us interpret it as a gradient zone. A correlation with the 'Hales gradient zone', i.e. the boundary between spinel and garnet peridotites was our preferred interpretation.

The ALCUDIA experiment, later acquired northwards of the IBERSEIS profiles, also shows prominent sub-crustal arrivals. However, these reflections also appear locally in the vertical incidence dataset at 19 s TWT, further constraining the depth at which this feature is located. In addition, the ALCUDIA wide-angle dataset shows refractions that become first arrivals above 180 km. This suggests that this boundary features a positive Vp contrast, varying its character from a transition zone to a sharper discontinuity.

Integration of the information provided by the IBERSEIS and ALCUDIA datasets with older data from the ILIHA project, where a mantle feature was identified at similar depths, allows us to map a regional scale upper mantle discontinuity in southwest Iberia. Its Vp increase, sub-horizontal geometry and tectonic context indicate that it is probably related to a phase transition, likely the Hales discontinuity.

IASPEI (Seismology, Geophysics)

S08e - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

IUGG-5207

Automated picking of teleseismic P- wave polarization parameters at the German Regional Seismic Network.

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Body wave traveltimes are often analyzed for the investigation of crustal and upper mantle structure. In addition, P-wave polarization may yield valuable information on lateral heterogeneity and anisotropy close to the recording station. We applied polarization analysis to a large number of recordings to identify contaminations by noise and to study the dependence of the polarization attributes as a function of backazimuth and epicentral distance. We automatize the determination of P-wave polarization attributes by developing tools for the determination of the incidence angle, azimuthal deviation and linearity in different frequency ranges. The automation of the procedure provided robust estimates of the polarization parameters including quality measures if high quality data. We analyzed 20 years of broad band recordings at the German Regional Seismic Network. Vertical angles as well as azimuthal deviations of P-waves vary with frequency and are mainly a function of the backazimuth. Also time dependent sensor misorientations may be detected. The azimuthal deviations of the P-waves polarization direction have been investigated and a fast direction of the azimuthal anisotropy has been determined by harmonic analysis. In particular the agreement of the retrieved fast direction at each station of the seismic array Gräfenberg, point to a high consistency of the observations and to the robustness of the analysis method and its implementation. At the Gräfenberg-Array, the observed dependence of the polarization parameters on frequency points to a 3D-pattern of anisotropy within the crust, a fast direction of 20°N is determined in the lower crust with an associated uncertainty of about 8°.

IASPEI (Seismology, Geophysics)

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S08p-334

The thermochemical structure of the lithosphere and upper mantle beneath South China: Results from multi-observable probabilistic inversion

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We study the thermal and compositional structure of South China by jointly inverting Rayleigh wave dispersion data, geoid height, topography and surface heat flow with a probabilistic (Bayesian) Monte Carlo method. We find that the lithosphere is thin (85-150 km) beneath the South China Fold system and thickens over the Yangtze Craton to maximum thicknesses of up to 280 km beneath the Sichuan Basin. In agreement with geochemical signatures from East China mantle xenoliths, our inversion predicts that the lithospheric mantle beneath the South China Fold system and Yangtze Craton is highly fertile (Mg# ~ 88-90). Such fertile compositions, together with the relatively thin lithospheric thickness in the area, point towards a widespread metasomatism/refertilization event. We suggest, as others have, that a flat-subduction episode and subsequent slab removal may have triggered both the delamination of the lowermost part of the subcontinental lithosphere and the generation of asthenospheric melts that metasomatized (refertilized) the remaining lithospheric mantle. Inconsistencies among geophysical observations and anomalously fertile compositions for the Sichuan Basin indicate that this region may be currently affected by small-scale convection or delamination processes. Alternatively, the anomalous observations may be associated with an eastward push of Tibetan lithosphere beneath the Yangtze Craton.

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S08p-335

Lithosphere structure underneath the North China Craton inferred from elevation, gravity and geoid anomalies

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The North China Craton (NCC) is a classical example of ancient destroyed cratons. The NCC experienced widespread thermotectonic reactivations in the Phanerozoic. Recent work suggested that the old craton has been significantly modified or destroyed during this process. However, most of the studies were confined to the Eastern NCC, the nature and evolution of the lithosphere beneath the Central and Western NCC was less constrained due to the lack of data.

While, recent geodetic data, with the advantages of high resolution and coverage, offers an opportunity to study the deep structure underneath the whole NCC. Here we construct a lithospheric-scale 3D model based on the integration of regional elevation, gravity, geoid and thermal data together with available seismic data. The combined interpretation of these data provides information on the density and temperature distribution at different depth ranges.

In the Eastern NCC, a rapid thickness decrease of both crust and lithosphere is reflected, concordant with abrupt changes in surface topography and Bouguer gravity anomaly. Our results together with the widespread magmatic rocks suggest that the Eastern NCC has experienced significant destruction of the lithospheric mantle with substantial modifications and thinning of the crust. In the Central and Western NCC, the generally thick and 'cold' lithosphere suggests that the cratonic mantle root is preserved in the central and western NCC, in agreement with the relatively low heat flow, rare magmatic activity and long-term tectonic stability observed at the surface, with some areas mildly modified as indicated by thin lithosphere.

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S08p-337

Shallow velocity structure of the Dharwar craton in southern India and its geotectonic implications

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It is essential to delineate the shallow crustal structure to extend the geological information from surface to depth for understanding the geo-tectonics of any region. We have applied the seismic tomography to seismic refraction data acquired along a 200-km-long line in the Dharwar craton of the southern Indian shield. The resulting crustal velocity model, which is also assessed with checkerboard tests, demonstrates that the shallow velocity varies between 5.7 to 6.4 km/s and is determined up to 10 km depth, probably due to very low-velocity gradients in the upper crust. Undulating high and low velocities in the top layers are terminated at a depth of 7-8 km, consistent with a probable detachment. We interpret the undulating upper-crustal velocity layers to represent a fold-thrust belt structure that developed during a collision in a transpressional tectonic regime, consistent with the model of Chadwick et al. (2000; 2007), which suggests oblique convergence and accretion of two crustal blocks in the region. The velocity structure also correlates reasonably with the geological units, which are distinct on the surface. We interpret relatively low velocities between the undulating layers as representative of faults that bound various tectonic domains.

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S08p-338

Architecture of West Bengal sedimentary basin, India: implications on breakup of East Gondwanaland

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The breakup of East Gondwana due to Kergulean/ Crozet hotspot activity and related upper Jurasic-lower Cretaceous Rajmahal volcanism has profound influence on the structure and tectonics of the whole region, and architecture of the west Bengal basin, India in particular. The present study aims at understanding the significance of East Gondwana breakup on the basin formation using seismic refraction data. The fine-scale subsurface velocity structures were derived using seismic tomography of first arrival refraction data along four profiles in the West Bengal sedimentary basin. The tomographic images depict smooth velocity variation from 1.8 to 4.3 km/s, corresponding to Recent, Quaternary and Tertiary sediments that have been deposited over the Rajmahal trap of 4.8 km/s velocity and the basement (5.8 km/s) down to a maximum depth of 16 km. The basement depth along the seismic profiles varies from 1km to 16 km, and it is shallow in the north & west and deep in the east and south, indicating a south-easterly dip of the basin in its pseudo 3-D configuration. The basement depth on the stable shelf of the basin in the west gently increases to about 8 km and dips to a maximum depth of 16 km in the deep basinal part within a short distance in the east. This abrupt increase in sedimentary thickness represents the Eocene Hinge zone / shelf break of the West Bengal basin. The basaltic Rajmahal traps identified in the present study may be related to the mantle plume activity, which is responsible for the breakup of East Gondwana during the Cretaceous time. Origin of the Eocene shelf break could be related to either Himalayan orogeny or rifting of east Gondwana.

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Structural model of the lithosphere-asthenosphere system and deep dynamics beneath the Qinghai-Tibet Plateau and its adjacent areas

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The Qinghai-Tibet Plateau is very complicated with different tectonic units in the place of the continent-continent collision between the Indian and Eurasian plates. Here we reconstruct the main features of the structure of the crust and upper mantle from surface wave tomography in order to understand the modality of the convergence and collision process. We collected long period and broad-band seismic data from the global and regional seismic networks surrounding the area. After preprocessing, group velocities of fundamental mode of Rayleigh waves are measured using the frequency-time analysis (FTAN). Combining the published dispersion data, a 2-D surface-wave tomography method is applied to calculate the lateral variations of group velocity distribution at different periods, in the range from 8 s to 150 s. The Hedgehog non-linear inversion method is performed to obtain shear wave velocity (Vs) versus depth models of the crust and upper mantle for 181 cells, with size 2º×2º. In order to identify the cellular representative models, we applied the Local Smoothness Optimization method (LSO). Fairly detailed structural models of the lithosphere-asthenosphere system have been defined. The variation in thickness of the metasomatic lid may suggest that the leading edge of the subducting Indian slab reaches up to BNS. The crust is very thick in the Qinghai-Tibet Plateau, varying from 60 km to 80 km. The lithospheric thickness is thinner (125-160 km) than its adjacent areas. Its asthenosphere is relatively thicker, varies from 100 km to 200 km. The study is supported by the Chinese National Science Foundation (41274062, 40804009), Italian MUR and University of Trieste in the framework of the Internationalization PhD Program (Prot. II04A1CHC8).

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S08p-340

P and S-wave velocities in weak anisotropic rocks

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Studying seismic anisotropy of lithospheric rocks by either lab or field measurements one have to describe the velocity anisotropy in terms of elastic moduli of rocks that can be much complex then for isotropic case. Assuming that rocks mostly exhibit weak anisotropy several approaches were introduced by Thomsen (1986), Tsvankin (1997) and Ohanian et al (2006) to simplify the velocity relation to propagation direction in transversely-isotropic (TI) and orthorhombic (OR) media respectively. In our work we present the extensive description of weak anisotropy approximation for phase and ray velocities of P and S-waves using the results obtained by Tsvankin (1997) for the general case of OR symmetry. It is also shown that the requirement of weak anisotropy leads to OR symmetry or higher. The effect of thin layering and the presence of crystallographic texture of rock-forming minerals as the main sources of weak anisotropy are considered.

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S08p-341

Tomoigraphic Evidence of the Tan-Lu fault zone in the Bohai Sea of China

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The Tan-Lu fault zone (TUFZ) is a N-S trending strike-slip fault zone in the eastern China. It is over 2000 km long and ~50 km wide and thought to be a lithospheric-scale fault zone cutting throughout the crust into the upper mantle. Mantle-source magma intrusions had taken place beneath it since late Tertiary. Within the Bohai Sea of China, the TUFZ is covered by thick Cenozoic sediments and truncated by the NW-trending Zhangjiakou-Penglai fault zone (ZPFZ) in the south. Geophysically, the TLFZ plays as a gravity boundary between negative anomalies in the east and positive anomalies in the west. A positive magnetic anomaly belt is observed along the TLFZ. Seismic activities are mostly distributed on its southern parts that intersect the ZPFZ. In order to determine the nature of the TLFZ in the deep crust and relate it with regional dynamics, using P-wave arrivals from earthquake data recorded by permanent stations around the Bohai Sea, we performed local tomographic study with aim to investigate the crust and uppermost mantle structure of the Bohai Sea. Results show that the trending of the deep structure of the sea area is parallel to the TLFZ. A prominent feature is that the TLFZ is underlain by a high-velocity mid-lower crust. This is particularly clear in the northern and central Bohai Sea, while the lowermost crust is characterized by a thin high-velocity layer, which reflects evidence of the early volcanism and mantle magma intrusions. Nevertheless, in the southern Bohai Sea, the trending of the structure in the mid-lower crust deviates from the TLFZ. Together with seismic activities, it supports the eastward extension of the ZPFZ from eastern inland into the Bohai Sea. This fault zone is probably only limited in the crust, not penetrating into the upper matnle.

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S08p-342

Fabrics of the Northern Fennoscandian lithosphere inferred from 3-D seismic anisotropy

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Passive seismological experiment LAPNET (2007–2009) provided data for structural studies of the upper mantle beneath the northern Fennoscandia. We concentrate on evaluating the large-scale anisotropy fabrics in the upper mantle from (1) splitting of SKS waves and their particle motions (PM) (Vecsey et al., Tectonophysics 2008), (2) directional terms of relative P-wave travel time residuals and (3) joint interpretation/inversion of body-wave anisotropic parameters (Plomerova et al., Solid Earth 2011).

The study confirms that the mantle lithosphere consists of several blocks with olivine fabrics differently oriented in 3-D (Vecsey et al., Tectonophysics 2007). Geographic variations of seismic-wave anisotropy delimit individual domains of the mantle lithosphere, each with a consistent fabric orientation. The domains are sharply bounded both in the Proterozoic and Archean provinces and can be modelled in 3-D by peridotite aggregates with dipping lineation a or foliation (a,c). These findings allow us to interpret the domains as micro-plate fragments retaining fossil fabrics in the mantle lithosphere, reflecting thus an olivine lattice-preferred orientation created before the micro-plates assembled. A boundary between regions with positive and negative velocity perturbations in teleseismic P-wave tomography shifts westward with depth. The shift can indicate an inclination of the Baltic-Bothnia Megashear Zone and reflect a wedge like structure of the Proterozoic-Archean transition similarly to that in the south-central Finland (Plomerova et al., 2006). Studies of fossil anisotropy preserved in the mantle lithosphere contribute both to mapping the lithosphere-asthenosphere boundary and deciphering the boundaries of individual blocks building the continental lithosphere.

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S08p-343

INTEGRATED DENSITY MODELLING OF THE LITHOSPHERE IN CENTRAL EUROPE

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The contribution presents new results related to the lithospheric structure and dynamics of the Central Europe. We applied three different methods: 1D automatic modelling, 2D integrated geophysical modelling and 3D inversion. These methods are similar concerning the used databases but differ by used processing and interpretation. The 1D automatic modelling provides a very first overview of the studied region. The 2D integrated modelling of the lithosphere combines the interpretation of surface heat flow, geoid, gravity, and topography data in the Central Europe. This approach is able to constrain the complicated lithospheric structures of the studied region better than interpreting each data set on its own. We present four 2D integrated models of the lithosphere in the Central Europe. Finally, based on the 3D Inversion algorithm, we present the geophysical models of the lithosphere in the Carpathian–Pannonian region. The algorithm returns the density structure of the lithosphere from joint inversion of free air gravity, geoid and topography data based on a Bayesian approach. The models are based on different input data sets and constrained by different a priori data. Based on our modelling we cannot confirm the extreme thinning (less than 70 km) of the Pannonian Basin lithosphere. The results show the increasing trend of the lithospheric thickness along the Carpathian arc from the Western Carpathians toward the Eastern Carpathians which confirms the previous theories about the propagation of subduction process. The models show that the Moesian Platform is overthrust from the North by the Southern Carpathians and from the South by the Balkanides. The south-eastern edge of the Pannonian Basin based on 3D inversion indicates unexpected and surprisingly thin lithosphere.

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S08p-344

Stress evolution and seismic hazard on the Maqin-Maqu segment of East Kunlun Fault zone from Co-, Post-, Inter-seismic stress changes

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The East Kunlun Fault zone, striking E-W to WNW-ESE, has been recognized as one of the largest and most active left-lateral strike-slip faults in the China continent. Presently, the Maqin-Maqu segment (MMS) is recognized as a seismic gap on the East Kunlun Fault. Since several highly-populated counties are close to this region, understanding stress transfer and accumulation along this segment is important for hazard assessment along the MMS. In this study, we calculated the stress evolution along the MMS of the East Kunlun Fault zone during 1879-2008 by integrating coseismic effects, viscoelastic relaxation and tectonic loading. It is observed that the stress accumulation on the western part of the Maqin segment has been effected by the 1937 Tuosuo Lake earthquake, the stress on the eastern part of the Maqin segment. Also, the western part of the Maqu segment was relaxed by the 1947 Dari earthquake, and the stress loading on the eastern part of Maqu segment was increased by both the 1879 Wudu and 2008 Wenchuan earthquakes. It is observed that, compared to co-seismic static stress changes, the post-seismic viscoelastic relaxation process has played a more important role on stress accumulation in the Maqu segment. The increased stress on the Maqin and Maqu segment is consistent with tectonic loading over 160 and 250 years, respectively, which we expect will lead to future earthquakes and associated seismic hazard on these segments.

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Geoacoustic provinces in the southwestern part of the Ulleung Basin, East Sea

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Total 157 piton and box core samples were collected and analyzed for characterizing physical properties and geoacoutic provinces of surficial sediments in the southwest part of the Ulleung Basin, East Sea. The results and distribution pattern of surficial sediment texture, physical and acoustic properties reflected well the sedimentary environment in the study area. The inner shelf and basin slope in this study are dominated by fine grained sediments and show high porosity and water content, with low bulk density and velocity. The trough of Korea Strait and outer shelf composed of coarse grained sediments show low porosity and water content and high bulk density and velocity. Based in situ velocity and sediment properties, the study area is divided into five provinces: (1) Province IA is hemi-pelagic mud partially mixed with intermittent sandy sediments which are derived from the outer shelf due to slide/slump or mass flow (in situ velocity: 1427 m/s, mean grain size: 8.4 Φ, bulk density: 1.24 g/cm^3, and porosity: 84%), (2) Province IB is covered with muddy sediments that are deposited during Holocene (1442 m/s, 7.9 Φ, 1.35 g/cm^3, 78%), (3) Province II is marked by mixed recent and relict sediments (1477 m/s, 6.1 Φ, 1.53 g/cm^3, 68%), (4) Province III is dominated by coarse-grained relict sediments formed during Pleistocene (1560 m/s, 3.8 Φ, 1.77 g/cm^3, 54%), (5) Province IV (1668 m/s, 3.0 Φ, 1.91 g/cm^3, 46%) is consisted of more coarser sediments than Province III. Compressional wave velocity, mean grain size, and bulk density increase from Province IA to Province IV, whereas porosity and water content decrease from Province IA to Province IV.

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Crustal Structure of Southern Coast of Bahía de Banderas, Jalisco, Mexico

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The western margin of Mexico is one of the most active seismic zones in America. It is also a region where large earthquakes (M=8.2) have occurred with very destructive consequences, including the generation of big tsunamis. From a tectonic point of view, this region is highly complex due to the interaction of several tectonic plates, the processes of oceanic accretion in the East Pacific Rise and subduction in the Middle American Trench, and the major extensional fault segmentation within the Gulf of California. Up to now, the large earthquakes rupture area occurred in this region spans only the southern half of the area proposed in this study. This fact suggests that the northern Jalisco coastal area, including the Bay of Banderas, is also a zone of high seismic potential. Spanish and Mexican scientists investigated the western margin of Mexico at the collision zone between Rivera, Cocos and North American plates within the framework of TSUJAL project TSUJAL Project (Crustal characterization of the Rivera Plate-Jalisco Block boundary and its implications for seismic and tsunami hazard assessment) during 2014. Morphology of the deep bottom of Bahia de Banderas (Mexico) was obtained using multibeam bathymetry showing a central canyon 1000 m depth with a submarine network of ravines and gullies. A crustal P-wave velocity model for the southern coast of Bahía de Banderas was obtained using wide angle seismic data recorded by OBS and seismic stations for more than 150 km across Rivera Plate and Jalisco Block. Preliminary results with a shows oceanic crust with a 8 -10 km thickness and a low subduction angle (<12°) for this area. These results agree with seismicity reported by the Jalisco Seismic and Accelerometric Network (RESAJ) permanent seismic stations.

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S08p-347

Radial anisotropy of the Australian lithosphere and asthenosphere

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A new radially anisotropic shear wave model of the Australian upper mantle is constructed from multi-mode surface waves. 3-D distributions of SV and SH wave speeds are derived from multi-mode phase speed maps that incorporate the effects of finite-frequency and off-great-circle propagation. We used the vertical profiles of the isotropic (or Voigt average) shear wave speed to map the depth and thickness of the lithosphere-asthenosphere transition (LAT) underneath the Australian lithosphere. The estimated thickness of the Australian lithosphere is thicker in the west and becomes thinner in the eastern Phanerozoic region. The new anisotropic model shows the significant vertical and lateral variations of radial anisotropy in and underneath the lithospheric mantle. In the shallower depth above 80 km, strongly faster SH anomaly is found particularly within the suture zone in central Australia between cratonic blocks as well as in the eastern Phanerozoic region, which may reflect the frozen-in anisotropy due the past deformation in the uppermost mantle. In the mid-lithospheric depth below 90 km in the cratonic regions, the strength of radial anisotropy becomes weak. The depth of weakened anisotropy coincides well with the estimated depths of the mid-lithospheric discontinuity from body-wave receiver functions. In the asthenosphere, or below the estimated depth of LAT, the strongly fast SH wave speeds are found particularly beneath the wide areas of central Australia, which reflects the strong effects of horizontal shear beneath the fast drifting Australian continent.

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S08p-349

Upper mantle anisotropy around the ordos block in China and its geodynamic significance

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The Ordos is a stable block between the Eastern and Western China surrounded by active thrust belts and extensional graben systems. Investigations on the upper-mantle deformation and flowing pattern beneath the Ordos will help to illuminate how the different geodynamical processes affect the intra-continental deformation in China.

From five portable seismic arrays in the southern Ordos block, SKS and SKKS phases are used to estimate the S-wave splitting parameters. The results show distinct anisotropy in the upper mantle beneath the Ordos area. To the southwest of the Ordos, the orientations of anisotropy are NNW-SSE, which are subparallel to the thrust belt and boundary faults between the Ordos and the Northeast Tibetan Plateau, mapping a clockwise mantle flow induced by the eastward extrusion of the Northeast Tibetan Plateau and deflected by the Ordos block. To the south of the Ordos, mantle flow direction is nearly E-W, parallel to the strike-slip direction of the Weihe graben, indicating an eastward mantle flow from the NE Tibetan plateau to the eastern part of China. To the east of the Ordos, the direction of fast S-wave is changing slowly from NWW-SSE to E-W, perpendicular to the main tectonic direction in Shanxi graben system, showing an extension feature similar to that of the North China.

Above results illuminate much information on the mass deformation and migration in the upper mantle resulting from the interactions between the Ordos block and its surrounding dynamic systems. It can be seen that the thrust faults and extensional grabens around the Ordos block are the positions where the anisotropy shows obvious change. As the boundary area of different blocks, they are the key areas to adjust the transformation between different geodynamic systems.

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S08p-350

Crustal and mantle lithospheric structure of the Iberian Peninsula deduced from potential field and thermal modeling

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We investigate the lithospheric structure of the Iberian Peninsula and the lateral crustal density variations from a two-step approach: firstly we map the crustal and mantle lithosphere thicknesses in combination with elevation and geoid anomaly data together with the thermal field; secondly we compute the 3D gravity effect of the resulting lithospheric structure to highlight and discuss lateral density variations within the crust. Our results show that for the majority of the study area the resulting crustal thickness does correlate with the regional topography pattern. The highest average filtered topography –above 1500 m– show crustal thicknesses above 44 km with local values up to 50–52 km. Crustal thicknesses in the range of 36–40 km are obtained along the uplifted Alpine areas while a thinner crust is observed in the Tertiary sedimentary basins and in most of the Iberian Massif (28 to 32 km) with the exception of the anomalous NE–SW trending crustal thinning, from 30 to 24 km, in SW Iberia. Thick lithosphere –more than 130 km– is found along the Pyrenees, the Basque Cantabrian Basin, eastern/central regions of the Cantabrian Mountains and in the Betics whilst the thinnest lithosphere is found in the southernmost region of the Iberian Massif (80 km). The calculated residual gravity anomaly map shows that for most of the Iberian Peninsula residuals are in the range of -10 to 10 mGal; out of this range residual anomalies are interpreted in terms of crustal structures and geological domains.

IASPEI (Seismology, Geophysics)

S08p - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

S08p-351

Preliminary 3D electrical lithospheric structure of the Rajasthan, Northwest India and its tectonic implications

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Combined long period (30-30,000 s) and broad-band (0.001-1000 s) magnetotelluric (MT) data are being acquired in a series of temporary arrays deployed across Rajasthan, the NW part of the Indian subcontinent. Here we present the results of 3D MT modeling of data acquired during 2012-2015. The 3D inversion study used the full MT impedance tensor from 70 locations on a quasi-regular grid covering a rectangular area of 400 km x 350 km with an average spacing of ~55 km. The 3D resistivity depth slices retrieved using MT3DINV algorithm reveal extensive areas of high conductivity in the lower crust and shallow upper mantle regions to the west of the Delhi-Aravalli mobile belt. A reduced resistivity feature following the western edge of the Proterozoic Delhi-Aravalli mobile belt is imaged from mid-crustal level to upper mantle depths, indicating the Paleo-suture between Marwar and Bundelkhand cratons. High resistive Lithospheric column having more thickness compared to its neighborhood is inferred in the southwestern part of the study region. This region perhaps represents the Marwar craton. A low resistive anomaly is also seen at the base of lithosphere towards south of Mundwara and Sarnu-Dandali, the speculated locations of pre-Deccan eruption caused by the Reunion mantle plume. By and large shallow asthenosphere is imaged towards north as compared to south of 26^0N latitude.

IASPEI (Seismology, Geophysics)

S08p - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

S08p-352

Gravity anomalies and crustal density structure characteristics of profile Weixi-Guiyang,China

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Wei-Guiyang profile is located in southeastern margin of the Tibetan Plateau, where is the important lot for the Tibetan substance escape south-eastward. Using profile gravity data and GPS location data, and combining with regional geological structure and deep geophysical achievements inverse a more detailed crustal density structure characteristics of the gravity profile. The observational studies show that: the total amplitude difference change of Bouguer gravity anomaly of the profile is about $190\times10^{-5}ms^{-2}$, the segment variation shape looks like “oblique N”; The trend turning parts of the ratio of the elevation and gravity anomaly are at the core”axis” and the eastern side of Xiaojiang fault, which may be related to the development of pre-existing structure or the newborn structure; The profile crustal density structure can be divided into upper, middle and lower three layers, the average depth of the bottom boundary layers is about 20km, 35km and 51km respectively, Jinshajiang- RedRiver fault zone and Xianshuihe-Xiaojiang fault is the transition zone of the crustal structure; the crustal thickness is deep in west and shallow in east, it may be due to laterally squeezed of eastern tectonic syntaxis; Lower crust thickness variation is relatively large, it may play a major role for crustal thickening; Moho surface uplift near Huaping-Panzhihua and the existing high density body of the upper crust what play a role in blocking for the south east escape of Tibet Plateau substance and lateral squeeze of eastern tectonic syntaxis; the limited low-density thin layer in the middle crust is beneficial to its upper substance south-eastward escape and clockwise, and the eastward or north-eastward migration of its lower substance what is on the effect of the east structure.

IASPEI (Seismology, Geophysics)

S08p - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

S08p-353

Lithosphere structure in the southern Madagascar from receiver function and ambient noise surface wave dispersion analysis

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The geology of the western part of Madagascar is very different from that of the eastern part of Madagascar. The eastern part is dominated by Precambrian rocks; whereas the western part is characterized by sedimentary formations. The Precambrian rocks in Madagascar have several tectono-methamorphic units with age ranging from Archean to Neoproterozoic. Although Madagascar is now located far away from the major plate boundaries, potentially damaging earthquakes with magnitudes up to 5.9 have occurred in Madagascar. Also the present seismic activity indicates that some deformation is taking place there. Existing studies suggest that the lithosphere in Madagascar appears to be thin (< 120 km) compared to the nearby East African Lithosphere.
Between 2012 and 2014, 25 broadband and 23 short period stations were operated in Southern Madagascar extending from the East coast to the West coast. These stations cross different domains and are thus suitable for investigating the evolution of the Precambrian lithosphere and the effect of the Cenozoic and the recent igneous activity. We will present preliminarily results regarding the lithosphere structure in the southern part of Madagascar. Our interpretation focuses mostly on the contrast between the lithosphere structure in the Precambrian rocks and the basin formation in Madagascar and the local seismicity. Beneath the sedimentary formation, crustal thickness varies between 23 km and 30 km and the Vp/Vs ratio ranges from 1.79 to 1.85. In the Precambrian rocks, the Moho depth ranges from 30 km to 40 km, and the Vp/Vs’ ratio of the crust varies between 1.69 and 1.79. The crustal thickness in the western part of the Precambrian rocks is relatively thin (average 35 km) compared to those in the eastern part (average 39 km).

IASPEI (Seismology, Geophysics)

S08p - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

S08p-354

Estimating Dip-Slip Fault Parameters in the Wichita Uplift Region Using Gravity Gradients

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The tectonic setting of southwestern Oklahoma and northeastern Texas is an ideal example of an aulacogen, the result of a failed rift of the North American continent during the Paleozoic era (540 – 360 Ma). The Wichita Province forms the uplifted basement portion of this Southern Oklahoma Aulacogen (SOA). The major fault zones to its north and south are clearly evident in gravity gradient maps produced by the recently constructed Earth Gravitational Model 2008 (EGM2008). Fault parameters, such as the strike, dip angle, and location have been estimated primarily from profiles of seismic data and local gravimetry in the 1990s. New estimates are obtained here from the EGM2008 gradients and airborne gravity gradients in the area using optimal, least-squares estimation based on the Monte Carlo technique of simulated annealing. We find general agreement with the previously constructed geologic models and thus demonstrate the utility of gravity gradients in mapping fault zones.

IASPEI (Seismology, Geophysics)

S08p - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

S08p-355

High resolution moho topography beneath central and eastern Betics, western mediterranean region, by receiver function techniques

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We map the lithospheric structure under the central and eastern Betics (western Mediterranean region) interpreting P-receiver functions obtained from two dense seismic profiles (HIRE and Transcorbe profiles of ~120 km and 160 km of length, respectively). The goal is to study the lithospheric structure and its variations between the different geological domains, from the Alboran domain in the south (metamorphic rocks), the External zones (sedimentary rocks) and the Variscan terrains of the Iberian Massif in the north. One of the profiles (HIRE), North-South oriented, crosses the Sierra Nevada Mountains, one of the prominent features in the Western Mediterranean tectonic region with the highest topography of the Iberia peninsula (~3400 m). The spacing between stations, around 2km, allows mapping with high accuracy of the variations of the crustal structure. We observe a sharp Moho step of ~15 km under the Internal zones of the Alboran domain coinciding the thinner crust with the highest topography along the profile. This agrees with the prior hypothesis about the lack of crustal root underneath Sierra Nevada Mountains and opens a question about the source of the dynamic compensation of its topography. Previous studies showed that the Iberian crust understrust the Alboran domain under its contact with the External zones observing the presence of slab-type feature of Iberian lithosphere at the western Betics while tearing of this Iberian slab is proposed at central and eastern Betics. We observe that the Iberian crust undertrust the Alboran domain and terminate sharply under the contact between the Alpujarride and the Nevado-Filabre complexes (Alboran domain).

IASPEI (Seismology, Geophysics)

S08p - S08/S08a Lithosphere Structure and Dynamics: Open session, Lithospheric Structure - LAB Observations and Models

S08p-356

Time-term analysis of crustal structural variations from first arrival data

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The time-term method is a simple travel time inversion for determining two and three dimensional structure by using refraction data. The method also can estimate a robust basement velocity under the complicated surface structure. In this study, we identified P arrival times from 10 explosions were set off by TAIGER (TAiwan Integrated GEodynamics Research) project and collected P arrival readings from earthquakes were determined by Taiwan Central Weather Bureau Seismic Network (CWBSN). We used these arrivals to estimate the time-term values of the sediment-basemast interface (interval 50 to 85 km) and the Moho (larger than 180 km). The values ranged respectively from 0 to 1.6 sec and 4.5 to 8 sec. Both of the results correlate well with the major geologic units: low values for stations on the mountains range are underlain by high velocity rocks, and high values on the the western Taiwan are underlain by low velocity sediments. The P-wave velocity of interface and Moho were found to be ~5.8 km/s and ~7.7 km/s, respectively.

IASPEI (Seismology, Geophysics)

S08ba - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-0348

Do passive continental margins host aseismic plate boundaries?

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The recognition of lithospheric segments, within the framework of plate tectonic hypothesis, is based mainly on the nature seismic activity along its boundaries and the characteristics of its movements (divergent, convergent, transform or diffuse). This approach however overlooks the possibility that aseismic plate boundaries may be present beneath continent – ocean transition zones. Here we examine variations in heat flow as a convenient tool for mapping such plate boundaries. The continental margin of eastern Brazil was selected as the test area. With a novel approach in analysis of temperature gradient and heat flow data it has been possible to identify the presence of a narrow geothermal belt (>5000 km long) overlying the zone of continent-ocean transition, along the east coast of Brazil. The main characteristics of this anomaly (with magnitudes of 70 to 120mW/m^2 and widths not exceeding 200 km) are compatible with those produced by heat sources at depths of basement complex beneath the sediment cover along the continental margin. It implies that contact zones between continental and oceanic segments of the lithosphere allow escape of abnormal quantities of Earth's internal heat, in a manner similar to those occurring along divergent plate boundaries. The difference is that "tectonic bonding" between lithospheric segments is relatively weak along passive margins. Such zones are subject to episodes of passive upwelling of mantle material, which trigger only micro-seismic activity. Since most of the "contact plate boundaries" had their origin at distant spreading centres, these may be considered as the most dynamic plate boundaries on the surface of Earth.

IASPEI (Seismology, Geophysics)

S08ba - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-0753

Integrated geophysical GIS&RS models of the of Lithosphere - part Uzbekistan

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An integrated approach has been applied to reveal the structure of orogenic Lithosphere in Middle and South Tien Shan, Gissar regions and Aral-Ustyurt and Amu Darya basins in Uzbekistan. The created GIS&RS models show the spatial interrelations between the peculiarities of the lithospheric structures associated with sedimentary basins and intrabasinal areas of the region and the geodynamic processes occurring there. Some of these structural discontinuities are poorly expressed in surface geology, but can be detected by remote sensed methods, as well as by magnetic and gravity anomalies. This study was made with complex deep seismic sounding profiles, which are characteristic of the upper mantle rocks, related to morphology of bodies, their physical properties, consisting mainly in their contrasting values for contiguous blocks, and general increased velocity and density of the rocks contain. The cross-section zonality by geophysical and RS data caused by presence of hidden long-living basement faults of the northeast direction alongside with longitudinal zonality, caused by sublatitudinal orientation of main structures in Southern Tien Shan plays important role in tectonics and genesis ore and oil-gas deposits of the given region. Mapping of these zones helps select new ways in the search for mineral deposits. Construction of the integrated model spatial database using ESRI ArcGIS10.1 and RS methodologies, combining (i) the 3-D DEM model on the base of SRTM images; (ii) 3-D models of surfaces of basement and Moho from reinterpretations of the potential fields and DSS profiles; (iii) geological maps of Gissar, Aral-Ustyurt regions and Middle and South Tien Shan; and (iv) borehole subsidence analysis information, integrating with the regional geophysical data.

IASPEI (Seismology, Geophysics)

S08ba - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-1975

Lithospheric structure in eastern Australia from seismic tomography

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The eastern third of the Australian continent comprises an assemblage of Palaeozoic orogens that formed outboard of the proto-Pacific margin of East Gondwana. The tectonic evolution of this region is complex, with a number of studies demonstrating that the accretionary process that built the orogens involved much more than simple subduction of oceanic lithosphere along a continental margin. The lack of Palaeozoic outcrop due to more recent cover has added to the challenge of unravelling the tectonic history of this region. We use ambient noise and teleseismic data from WOMBAT, the largest transportable seismic array in the southern hemisphere (over 700 stations deployed to date, with a maximum station spacing of 50 km), to image the 3-D velocity structure of the crust and mantle lithosphere beneath a large region of eastern Australia that extends from Victoria up to central Queensland. Our results reveal a variety of striking features, including: (1) a north-dipping low velocity anomaly that extends to ~250 km depth beneath the Newer Volcanics Province, a Quaternary intraplate basaltic province in western Victoria; (2) a high velocity anomaly in the mantle beneath the Curnamona Province, a roughly circular-shaped piece of Archean lithosphere that forms an easterly salient into Phanerozoic Australia, and (3) an extensive high velocity anomaly beneath the Hay-Booligal Zone, a region containing Silurian-Devonian felsic volcanic rocks and granites buried beneath sediments, which is consistent with the idea that it may be floored by a fragment of continental lithosphere that was once part of the east Gondwana margin.

IASPEI (Seismology, Geophysics)

S08ba - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-2239

The Crust beneath Morocco: From the Surface Topography to the Upper Mantle

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The most characteristic topographic features of Morocco are the Atlas Mountains and the Rif Cordillera. These two orogenic belts are the response of different geodynamic processes acting at lithospheric scale caused by the complex plate interaction between Africa and Europe. It is a broad zone of deformation that includes: the Betics, the Rif Cordillera, the Alboran basin and, the Gibraltar arc. The area is characterized by a relatively large amount of earthquake activity at various depths. Within the last decade a large international effort have been devoted to the area to constrain the structure, composition and tectonic scenario from south of the Atlas to the Betics, across the Rif cordillera and the Alboran basin. Multidisciplinary research included: earthquake recording with broad band temporal deployments and, controlled source seismic acquisition of wide-angle seismic reflection data. A transect from Merzouga across the Gibraltar Arc and into the Iberian Peninsula and, a nearly regular grid of BB were acquired. The data constrains the litospheric structure and provides seismic P-wave velocity models from the coast across the Rif and the Atlas. The crust features a moderate crustal root (40 km) differing from the 35 km thickness value observed at both sides. Travel time inversion positions the root just south of the High Atlas defining a thrusted mantle wedge. A prominent crustal root (over 50 km) located beneath the external Rif is identified by the wide-angle data and receiver function studies. To

the east the crust thins rapidly by 20 km across the Nekkor fault zone. On shore-offshore records reveal complexities in the transition to the Alboran basin.

IASPEI (Seismology, Geophysics)

S08ba - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-2949

Rift structure and sedimentation history of the eastern continental margin of India

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The Eastern Continental Margin of India (ECMI) has carved out as a passive continental margin from Eastern Gondwanaland, then continued to remain without major magmatic inclusions. Subsequently the Indian subcontinent collided with Asian continent ~40 Ma, since then the subcontinent is being pushed beneath the overriding Asian continent, the process eventually led to formation of highest mountain range, the Himalayas. The mountain range and the then prevailed Asian climate have interacted leading to initiation of erosion process in Himalayan and Tibetan Plateau regions and transportation of terrigenous material to Arabian Sea and Bay of Bengal to form Indus and Bengal fans, respectively. Therefore the Bay of Bengal is a unique place to obtain sediment records for understanding linkages between the Himalayan tectonics and Asian climate and time of initiation of Bengal Fan deposition.

High quality seismic data acquired from the Indian shelf to deep-water region were investigated. The basement morphology in the vicinity of ECMI depicts Gondawana grabens, rift-related faults, rifted basins, etc. The margin is traversed by coast-perpendicular major graben structures as an extension of onshore rift zones and continue to offshore, where they get abut against the proto oceanic crust. In deep-water region, the 85°E Ridge is identified as an elevated feature having >3 km relief from the adjacent basement floor. A remarkable increase in sediment discharge observed at Oligocene-Miocene time (~23 Ma) provides an important age marker for the commencement of Bengal Fan sedimentation. An abrupt change in sediment deposition in the Bay of Bengal at Oligocene-Miocene time has strong

linkages with the rapid uplift of Himalayas and establishment of present-day Asian monsoons.

IASPEI (Seismology, Geophysics)

S08bb - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-1993

Stress inversions of focal mechanisms with application to the West Bohemia swarm region, Czech Republic

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Stress inversions from focal mechanisms require knowledge of which nodal plane is the fault. If such information is missing, and faults and auxiliary nodal planes are interchanged, the stress inversions can produce inaccurate results. We test accuracy of several stress inversions on synthetic data. We show that retrieving the principal stress directions is usually reasonably accurate even when the selection of fault planes in focal mechanisms is incorrect. However, the shape ratio is more sensitive to the proper choice of the fault. Substituting the faults by auxiliary nodal planes introduces errors particularly when using Michael's method (1984) and Angelier's method (2002). In the Michael's method, this difficulty can be removed by applying the fault instability constraint and calculating stress in iterations. As a byproduct, the fault orientations and overall friction on faults can be determined. The stress inversions of focal mechanisms are exemplified on data from the West-Bohemia swarm area, Czech Republic. The faults identified by the joint stress inversion are close to the principal faults delineated by foci clustering. The main activated faults are optimally oriented with respect to tectonic stress. They are characterized by fault instability of 0.9 or higher and produce shear earthquakes. In the Mohr's diagram, shear and normal stress on faults are concentrated in the area of validity of the Mohr–Coulomb failure criterion. The other fault segments are slightly misoriented. They have lower instability and are probably more tensile. They are activated most likely by the local redistribution of Coulomb stress during swarm activity.

IASPEI (Seismology, Geophysics)

S08bb - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-2198

Significance of crustal stress / strain patterns determined from focal mechanism solutions and geodetic movements of the Indian Plate interior

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Focal mechanism solutions of 102 data of >5 Mw earthquakes of Indian plate interior indicate P-axis plunge of 11° towards N340°, T-axis plunge of 11° towards N240°, and N-axis plunge of 88° towards N090°. Such a solution is indicative of regional strike-slip deformation to be predominant in the Indian plate interior. However, most of the seismic events were of either reverse fault or normal fault mechanism, with oblique components. Strain analysis of the Indian plate interior using geodetic data indicates effects of two-different orders of deformations: regional and local. The first-order strain rate curve has peak of compressional strain at N018° and extensional strain at N08°. These two are interpreted to be effects of compression across the Himalayan orogen at the northern margin and slab pull along the eastern margin. Both the strain rates are of the order of ~5 X 10^{-9} per year. Local extreme strain rates of ~200 X 10^{-9} per year are superimposed on these regional patterns. The roles of Riedel shears in localizing very high strain rate of second-order are brought out from this analysis. The depth distributions of seismic events of the Indian plate interior show >40% of the events at a depth of >15 km; out of which 15% events occur at depths between 30 and 43 km. Such high crustal rigidity can be explained by the strain-hardening mechanism developed by very high strain rate deformation. The case study of the Kachchh region in the western part of India confirms similar patterns. The 26 January 2001 Bhuj earthquake event can be explained in a manner similar to the regional pattern.

IASPEI (Seismology, Geophysics)

S08bb - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-3041

Geodynamics arguments around the IASPEI excursion in Southern Sweden 2013 on postglacial earthquakes

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Postglacial uplift is important for stress and strain in Scandinavia. But the World Stress Map project gave convincing evidence, that plate motion is responsible for the dominating stress. The uplift is on the other hand well recorded via geodesy and geology, in time scales of hundreds and thousands of years. Investigations are these years concerned with the stress-strain relationships. Large earthquakes occurred right when the Ice Cap left Scandinavia around 9.000 years ago, but how long did its effects last? This was the topic of the seismology excursion in southern Sweden in connection with the IASPEI meeting in Gothenburg 2013. Claimed palaeo-earhquake sites of younger age were visited. The outcome of the excursion was shortly said: “possibly earthquakes, but not probably”. The best possible strain fields from geodesy and geology are found and elaborated on. Some suggested large irregularities are discarded with convincing arguments.

IASPEI (Seismology, Geophysics)

S08bb - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-3825

Intraplate stress field in South America from earthquake focal mechanisms

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We updated the compilation of earthquake focal mechanisms in Brazil together with the sub-Andean region (mainly global CMT). All events in the sub-Andean region have reverse (majority) or strike-slip mechanisms. Focal mechanisms in Brazil show reverse, strike-slip and normal faulting. Focal mechanisms were grouped and inverted for the stress tensor. In the sub-Andean region, stresses are compressional, as expected, with the principal major compression (S1) roughly E-W, on average. A slight rotation of S1 can be observed and is controlled by the orientation of the Andean plateau. In the sub-Andean region, the intermediate principal stress (S2) is also compressional, a feature not always reproduced in numerical models found in the literature. In mid-plate South America stresses seem to vary in nature and direction. In SE Brazil and near the Chaco-Pantanal basins, S1 tends to be oriented E-W with S2 approximately equal to S3. This stress pattern changes to purely compressional (compressional SHmax and Shmin) in the São Francisco craton. A rotation of SHmax from E-W to SE-NW is suggested towards the Amazon. Despite the few available data, a 2000km long uniform field is suggested in mid-plate South America. Along the Atlantic margin, stresses are affected by coastal effects due to continent/ocean spreading as well as flexural effects from sediment load at the continental margin. This coastal effect tends to make SHmax parallel to, and Shmin (usually S3, tensional) perpendicular to the coastline. Few breakout data and in-situ measurements are available in Brazil and are generally consistent with the pattern derived from the earthquake focal mechanisms. Comparisons with new numerical models of global stresses based on CRUST1.0 and basal tractions will be presented.

IASPEI (Seismology, Geophysics)

S08bb - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-3854

Spatio-temporal changes of reservoir properties and seismicity at The Geysers geothermal reservoir, CA, USA

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Spatio-temporal changes of the ratio between the seismic P- and S-wave velocities (Vp/Vs) are investigated to study the correlation of the reservoir properties with injection history and observed seismicity $M \geq 4$. A careful selection of subsets of seismicity from different years is necessary to compare the 3D seismic tomography results. The resulting temporal changes include increases in Vp/Vs that correlate with the locations of the largest injection wells in the central and south-east Geysers and decreases in Vp/Vs that are confined to the north and north-west Geysers and correlate with the high-temperature reservoir thus indicating sustained boiling of water to steam. It was found that an aggregate change of the pore fluid from vapor to liquid in conjunction with a slight temperature decrease best describes the observed temporal changes in seismic velocities. In contrast, the observed changes are independent of the observed pore pressure changes in the reservoir. Spatial correlation of Vp/Vs to larger magnitude events indicates that most $M \geq 4$ events are located along boundaries that delineate the transition zone from water to steam. Because the majority of the $M \geq 4$ events have a statistically significant isotropic component, it is conceivable that the isotropic part of the source rupture processes is initiated by first, tensile cracks and second, a sudden volume change associated with water flashing to steam.

IASPEI (Seismology, Geophysics)

S08bb - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-5471

Constraints on endglacial rupture mechanics from estimates of the current stress field

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At the end of the latest glacial period, some 10,000 years ago, northern Fennoscandia experienced more than a dozen large earthquakes, with magnitudes reaching Mw 8. As this is an intraplate region, where earthquakes today are mostly below magnitude 4, it appears as though the stress field 10,000 years ago must have been significantly different. Glacial isostatic adjustment models of the stress evolution during a glacial period indicates that although a 3 km thick ice sheet may induce vertical and horizontal stresses on the order of 30-40 MPa in the upper crust, induced differential stress are significant mostly toward the end of deglaciation. This is because the melting of the ice sheet, decreasing the vertical stress, is much more rapid than the rebound of the subsidence bowl, which reduces the induced horizontal stresses. The models also show that for faults to be destabilized, glacially induced stresses and background (tectonic and other) stresses must match and add constructively. Here we present new data on the current stress fields along the Pärvie and Burträsk endglacial faults in northern Sweden. As the faults are currently active with smaller earthquakes we estimate the stress fields from the inversion of earthquake focal mechanisms. The Pärvie events indicate a mostly reverse state of stress while the Burträsk events seem to favour a more strike-slip field. Comparing these stress estimates with models of the earthquake induced stress fields, tectonic reloading and the stresses required by the GIA models for earthquake rupture we investigate how the large endglacial earthquakes may have ruptured.

IASPEI (Seismology, Geophysics)

S08bc - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-0294

Coseismic stress change in frontal prism during the 2011 Tohoku-oki earthquake examined from the Japan Trench Fast Drilling project

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The 2011 Tohoku-oki, Japan earthquake (Mw9.0) produced a maximum coseismic slip of >50 m near the Japan Trench. To investigate why the plate boundary fault between the subducting Pacific Plate and overriding North American Plate which caused the earthquake had such unprecedented large coseismic displacement and slipped to the trench, Integrated Ocean Drilling Program Expedition 343 (Japan Trench Fast Drilling Project, JFAST) drilled through the earthquake fault about one year after the earthquake. The plate boundary fault is located at ~820 meters below seafloor in the drilling site and has been identified as the slip zone of the Tohoku-oki earthquake. Borehole wall resistivity images show that borehole breakouts are available in a wide depth range above the fault but are not available below the fault. Breakouts are reliable indicators of the orientations of current maximum horizontal stresses and can also be used to constrain the horizontal maximum and minimum stress magnitudes. As results of breakout analyses, the maximum horizontal stress orientation highly varied in the upper part of the borehole, but has a clear preferred orientation in a northwest – southeast direction in the deeper part just above the fault. This orientation is approximately parallel to the direction of the Pacific Plate subduction. Stress magnitude constraints indicate that the post-earthquake stress states in the hanging wall are either in or close to the normal faulting stress regime. By inferring the pre-earthquake stress state and comparing with the constrained post-earthquake stress state, a significant coseismic stress change was interpreted. The stress change suggests an active slip of the frontal plate-interface consistent with coseismic fault weakening and a nearly total stress drop.

IASPEI (Seismology, Geophysics)

S08bc - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-3340

The geodetic three dimensional strain-rate field in Switzerland: New methods and results

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Nowadays continental drift, crustal deformations, and the strain accumulation can be determined and verified by geodetic means. However, this remains very demanding in the region of Switzerland, located in Central Europe, because of the very small yearly movements generating equivalently small yearly crustal distortions at a maximum of 25 nano strain per year.

Since many years the Swiss office of topography is carrying out repeated GNSS measurements on its first order network. The resulting time-series of coordinates together with the long-standing levelling time-series form the data base for the estimation of a coherent kinematic deformation field of Switzerland.

Thanks to further development of the ‚Adaptive Least-Square Collocation (ALSC)‘, which was devised at our institute, and the implementation of a physical crustal model it became possible to directly calculate a three dimensional strain tensor field by measurements at the Earth’s surface, e.g. GPS and levelling. Strain-tensors thus obtained reveal a very high conformity with focal mechanisms determined from seismological data. For example the recently induced earthquake mechanism in the region of St. Gallen close to a geothermal test site is in agreement with the strain tensors determined by GPS-data.

The paper presents the method and shows results of geodetic determination of strain field in the complex tectonic setting of the Swiss Alps.

It is a novelty having shown the ability to predict focal mechanisms by GNSS data of very tiny long-term deformations.

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IASPEI (Seismology, Geophysics)

S08bc - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-4073

3D Stress and Strain Modelling in Nordland, Northwestern Norway

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The Nordland area in NW Norway is one of the tectonically most active areas in Fennoscandia. It exhibits patterns of extension, which are in contradiction to the first-order regional stress pattern which reflects compression from ridge-push. The regional stress field stems from the interaction of ridge push and GIA (glacial isostatic adjustment); the local stress field mainly results from gravitational stresses as well as the flexural effects of sediment erosion and re-deposition. Whereas the first three effects are fairly well constrained, the latter is only poorly known and is the focus of this study.

A number of data sets are collected within the project: Seismicity is monitored by a 2-year local seismic network. Surface deformation is recorded by a dense GPS network and DInSAR satellites. In-situ stresses are measured in a couple of relevant boreholes.

We develop 3D finite element numerical models of crustal scale, using existing geometric constraints from previous geophysical studies. Internal body forces (e.g. variations in topography) already yield significant deviatoric stresses, which are often omitted in stress models. We apply the far-field stress fields (GIA, ridge-push, sediment redistribution) as effective force boundary conditions to the sides or base of the model. This way, we can account for all stress sources at once, but can also vary them separately in order to examine their relative contributions to the observed stress and strain rate fields.

We constrain a best-fit model using the different seismological and geodetic data sets collected and compiled within the project. Major faults are included as pre-existing weakness zones. Their effects on stress localization are studied in connection to observed clusters of enhanced seismic activity.

IASPEI (Seismology, Geophysics)

S08bc - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-4915

Stress accumulation process in and around the Atotsugawa fault, central Japan, estimated from focal mechanism analysis and GNSS data

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The Atotsugawa fault is a 70-km-long dextral strike-slip fault in the central part of Japan. A remarkable linearment of earthquakes along the fault trace and a sharp bend of the Jintsu river due to dextral fault motion make it one of the best known active fault in Japan.
We estimated 275 focal mechanisms from P-wave first-motion polarities of small earthquakes obtained in an extensive seismic survey during 2004–2008 in and around the Atotsugawa fault where ongoing dextral shear strain concentration has been observed. Along the fault trace, the azimuth direction of P-axes is oriented WNW–ESE, which agrees well with previous studies. Around the western end of the Atotsugawa fault, a local stress disturbance is observed. The azimuth directions of the P-axes are parallel to the fault trace on the northern side of the fault and perpendicular on the southern side. The regional stress disturbance is also detected by stress inversion analysis. The azimuth of the maximum principal stress axis systematically rotates counterclockwise as the distance from the fault trace decreases. The similar pattern has been reported for the San Andreas fault (e.g., Hardebeck and Hauksson, 1999). These local and regional stress disturbances are simultaneously explained by a cumulative slip deficit in the shallower portion of the Atotsugawa fault relative to the surrounding fault surface (i.e., the eastern, western, and deeper extensions of the fault plane). We will discuss the validity of our model comparing it with the velocity field obtained from GNSS data densely distributed around the fault.

IASPEI (Seismology, Geophysics)

S08bc - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-5126

Modeling the geological and geodetic deformation in the Northeast Japan arc with earthquake cycle model

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In the Northeast Japan arc, the mismatch between different stages of the great earthquake cycle has been pointed out. The heights of marine and river terraces in the late Quaternary indicate permanent uplift of 0.3 mm/yr. On the contrary, geodetic observation of the 100 years before the M9, 2011 Tohoku earthquake shows subsidence up to 10 mm/yr on the Pacific coast. Coseismic deformation at the Tohoku earthquake shows further subsidence of 1 m. In terms of long-term balance, it remains a puzzle at which stage Northeast Japan turns to uplift. In this study, we construct a simple earthquake cycle model with dislocations to give a unified explanation to these variable deformation features in Northeast Japan. We assume a 40-km thick elastic surface layer over viscoelastic half-space as lithosphere-asthenosphere system, and a two-dimensional Eurasian-Pacific plate interface. The slip on the plate interface is decomposed into three components: steady slip of 80 mm/yr on the whole plate interface (steady subduciton), increase of slip deficit in the 500-km long locked region (interseismic locking) and periodic seismic slip occurring every 1000 years. We also take account of the advective effect of tectonic erosion of 3 mm/yr, following previous studies. We examined the extent of the locked region and found that in the case of the rupture stopping within the lithosphere at the depth of 30 km, the result well agrees with the observed pattern of the permanent uplift, the late interseismic subsidence, and the coseismic subsidence. In the earlier 200 years of the interseismic stage, the effect of viscoelastic response to the coseismic slip is dominant and can accommodate the late interseismic and coseismic subsidence.

IASPEI (Seismology, Geophysics)

S08bc - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

IUGG-5301

Modelling deformation, stress state, and mountain building in the island-arc crust of northeastern and central Japan considering heterogeneous thermal structure

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We model deformation, stress state, and mountain building in the island-arc crust of northeastern and central Japan under a compressional tectonic setting, with consideration of a thermal structure based on dense geothermal observations. We use a finite element method wirth viscoelasticity and elastoplasticity. We consider heterogeneous thermal structure and realistic petrological structure to define flow properties. Deformation of the northeastern Japan island-arc crust are firstly modelled under a compressional tectonic setting. We reproduce several elongate low-stress regions, where brittle-viscous transition zones are shallow, striking transverse to the arc.The low-stress regions correspond to hot fingers (high-temperature regions in the mantle wedge). The model produces regions with high uplift rates that correspond approximately to regions of high elevation (the Ou Backbone Range). Plastic fault zones are also developed along the foot of the range. The stress state, fault development, and mountain building innortheastern Japan are comprehensively explained in the model. Using the same method, a model of deformation and mountain building in the island-arc crust of central Japan is then developed. This is an area where several high mountain ranges have been formed by active crustal deformation. Dense geothermal observations indicate thermal anomaly in some areas. Numerical results show that under the compressional tectonic setting the mountains are reproduced along a high geothermal region. In particular, we can reproduce the Hida mountain range, where a geothermal anomaly exists. The newly developed model can thus reproduce mountains in consideration of the thermal structure, and the results are roughly consistent with observations.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-062

Using of seismic data for monitoring of the stress state in order to short-term earthquake prediction

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Development of seismic process causes a change in the stress state of the earth crust. As a result, in some areas may be increase in energy saturation of the crust, and the stress approaches to the strength limit. Monitoring of these parameters during 2009-2014 years for the territory of Southern California showed that they can be used to predict earthquakes.

The three-dimensional geomechanical model of Southern California was developed, including a mountain relief, fault tectonics and characteristic internal features such as the roof of the consolidated crust and Moho surface. The initial stress state of the model is governed by the gravitational forces and horizontal tectonic motions estimated from GPS observations.

The analysis shows that the three-dimensional geomechanical models allows monitoring of the changes in the stress state during the seismic process in order to constrain the distribution of the future places with increasing seismic activity. For this each new earthquake from USGS catalog was considered as the new defect of the Earth crust which has some definite size and causes redistribution of the stress state. As a result each half month we revealed locations of the maximal values of the stress state parameters: elastic energy density, shear stress, proximity of the earth crust layers to their strength limit. How follows from observations all four strongest events M=5.6-7.2 occurred in South California during the analyzed period were prefaced by the parameters anomalies in peculiar advance time of weeks-months in the vicinity of 10-50 km from the upcoming earthquake.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-063

Crustal images of the Southern Granulite Province of India and their geotectonic implications

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The Southern Granulite Province of India constitutes one of the most critical segments of the eastern Gondwana. Understanding the tectonic evolution and paleo-position of this region with respect to other continental counterparts therefore assumes global significance. Due to poor preservation of surface geology and contentious nature of the status of mega shear zones in the province, the geodynamic evolution of this terrain remained enigmatic. Many competing and conflicting models were therefore proposed on the evolution of this tectonically complex province. Recognizing that in such a multiple-deformed region of Precambrian antiquity, seismic images could be of great value; a network of seismic stations was installed to obtain the depth images over wide regions encompassing the well-known Palghat-Cauvery shear zone and lesser known Karur-Kambam-Painavu-Trichur shear zone. Our receiver functions and their H-κ stacking results delineate presence of distinctly different crusts, across NE-SW trending arm (on the surface) of the Karur-Kambam-Painavu-Trichur shear zone and Jhavadi fault. Similar analyses across Palghat-Cauvery shear zone area exhibit homogeneous character in terms of both crustal depth and average composition. The documented dissimilar petrological characters and Moho depths in the former region when integrated with other geological features such as the presence of ophifrags (ophiolite fragments) and occurrence of alkali syenites and carbonatites, suggest unambiguous presence of a geosuture. The seismological results across the Palghat-Cauvery shear zone are also significant, as they question some recent researches which argue that this zone marks the site of the fossil Mozambique Ocean, along which closure of the basin took place.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-065

Interseismic and fault rupture processes related to the 2008 Wenchuan earthquake: FEM modelling

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We make use of two-step modeling to simulate inter- and coseismic deformation within one seismic cycle by means of visco-elastic finite element method (FEM). The first step is to perform inversion to find the optimum modeling parameters by fitting the observed interseismic deformation. Then the model continues to produce a major seismic event to simulate the Wenchuan earthquake. The model results show that,to fit the observed interseismic deformation, it needs a “soft” lower crust and upper mantle beneath the Eastern Tibet, and a very strong lithosphere of the Sichuan basin. The computed interseismic strain accumulation in the lower crust beneath the eastern Tibet is much higher than that in the other regions. In particular, the elastic strain energy density rate accumulates very rapid in and around the Longmen Shan fault in the depth above 30 km that may explain why the great Wenchuan earthquake occurs in the region of such a slow surface deformation rate. Simulations of coseismic processes reveal relationships among slip acceleration, normal stress and shear stress changes on surface of the seismogenic fault. Coseismic slip appears to initiate in the gently-dipping section of the fault, but primary slips on both gently-dipping and steeply-dipping sections take place simultaneously. Minor fault slip accelerations decrease normal stress on fault surface to reduce frictional strength of fault, and in general increase shear stress on fault surface to enhance tectonic stresses on the fault to drive the fault further slips. Coseismic slip distribution also suggest that an important role of high-angle listric reverse faulting is to transfer overwhelming horizontal deformation of the Eastern Tibet into significant vertical displacement on fault during the Wenchuan earthquake.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-066

How Rigid are cratons? Relative Motion of cratons in Nubia Plate

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Plate rigidity is one of the main paradigms of plate tectonics and a fundamental assumption in the definition of a global reference frame as ITRF.

With the increasing number of GPS stations in Africa plate, geodetic studies has improved our understanding of rigidity of the plate. The presence of diffused band of seismicity, the Cameroon volcanic line, Pan African Kalahari orogenic belt and East Africa Rift suggest the possibility of relative motion of cratons within the Nubia plate. In the study we divide Nubia into three regions: Western (West Africa craton), Central (Congo craton) and Southern (Kalahari craton). Euler Vector formulation is utilized to study both internal rigidity and relative motion of the cratons.

All available GPS stations from the regions are used separately or combined in creation of six reference frames which enable us to understand the presence of the relative motion between the three cratons thus the stability of the Nubia plate as a whole. We utilize stations with at least 2.5 years of data between 1994 and 2014.

Given the small relative velocity, it is important to eliminate eventual biases in the analysis and to have a good estimation in the uncertainties of the observed velocities. We perform our analysis using Gipsy-oasis codes to generate time series. Velocities and relative uncertainties are analyzed using the Allan variance of rate technique, taking in account for colored noise. An analysis of the color of the noise as function of latitude and climatic region is also performed to each time series.

Preliminary results indicate possible slight relative motion of the cratons. However, the results are at the limit of the statistical significance and within the current velocity uncertainties the Nubia plate appears as single- rigid plate.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-067

Present-day crustal movement and strain of the surrounding area of Ordos block derived from repeated GPS observations

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The surrounding area of Ordos block located between Qinhai-Tibet block and north China block is one of the regions where the tectonic movement is most intensive in China mainland. Five large earthquakes with magnitudes of great than or equal 8 have occurred in this region since 1300. In order to investigate the crustal movement, strain distribution and fault slip rate in this region, GPS data observed from 2009 to 2013 were collected at 527 campaign–mode and 32 continuously operating GPS stations and used to calculate a precise and high spatial resolution velocity field and strain rate field. The results reveal that GPS sites within Ordos block move towards NEE, the rates of these sites change little, and the strain rates are between -0.01 and 0.01 ppm yr^{-1}. Tectonic movement and deformation of Shanxi rift is most intensive. The belt between Shanxi basin and its western mountains is under extension with strain rate of 0.01~0.03 ppm yr^{-1}. Meanwhile, the belt between Shanxi basin and its eastern mountains is under contraction with strain rate of 0.02~0.03 ppm yr^{-1}. The faults at the west boundary of Shanxi basin show left-lateral slip rates of 2~3 mm yr^{-1} and 2-3 mm yr^{-1} of normal-fault extension. However, the faults at the east boundary of the basin demonstrate right-lateral slip rates of 1~2 mm yr^{-1} and contraction rates of 1~3 mm yr^{-1}. Linghe hollow in the west of Haotao rift shows significant extensional deformation with strain rate of 0.02~0.03 ppm yr^{-1}. There is a 2.1 mm yr^{-1} of shortening motion in the southwest of Ordos block, while the velocity rates change little near Lupanshan fault system. It reveals that the fault system is locked in deep. Weihe fault system shows 1.0 mm yr^{-1} of left-lateral slip. Weihe basin is experiencing weak extensional deformation.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-068

Spatial heterogeneities of deviatoric stress in Kyushu, Japan, inferred from the focal mechanism and their implication for seismic activity

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We investigated the spatial variation in stress field in Kyushu Island, southwestern Japan. Kyushu Island is characterized by existence of active volcanoes (Aso, Unzen, Kirishima, Sakurajima) and shear zone (west extension of MTL). High activity of shallow earthquakes are found not only along active faults but also in the central area of the island where there are active volcanoes. We considered the focal mechanisms of the shallow earthquakes on Kyushu Island to determine the relative deviatoric stress field. Generally, the stress field was estimated by method of Hardebeck and Michael (2006), corresponding to a strike slip regime in this area. Minimum principal compression stress (sigma-3) with its direction of near north-south dominates in the entire region. However, the sigma-3 axes around the shear zone rotated toward normal direction to the zone. This result implied the shear stress reduction at the zone and was consistent with the right lateral fault behavior along the zone detected by strain rate field analysis for GPS data. On the other hand, a decline in the maximum principal compressional stress was found in the western part of the high seismicity area, in the middle of Kyushu Island; this may be caused by a thickening of the seismogenic zone, as estimated from D90 analysis.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-069

Borehole shape analysis and physical properties of the Costa Rica convergent margin sediments: IODP Exp. 334 (Sites 1378 and 1379)

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The breakouts on the LWD image data collected during IODP Exp. 334 were investigated from Holes U1378A and U1379A. Also, the diameter and width of borehole for two holes were calculated using GMI Imager software.

In Hole U1378A, borehole breakouts are detected in intervals between 110 mbsf to 438 mbsf. The breakout azimuth is slightly changed between 176 mbsf and 369 mbsf. Also, the average width of breakout varies from 52.46º to 70.55°. The maximum horizontal stress in Hole U1378A is oriented northwest–southeast direction. In Hole U1379A, borehole breakouts show different pattern compared to those of Hole U1378A. The borehole breakouts in interval between 300 mbsf to 890 mbsf are detected. The average width of breakout does not show significant variation (from 51º to 56º). Below 640 mbsf, the direction of borehole breakouts is slightly changed appearing a lot of breakouts. From borehole breakout analysis, we suggest that the maximum horizontal stress may be oriented northeast–southwest direction. This direction is probably related with complicated plate movement in this area.

Physical properties for core samples were measured using weight-volume method and MSCL. Grain size analyses for subsamples were also performed using Microtrac 3500 equipment. In Holes U1378B and U1379C, the water content and porosity generally decrease with burial depth. Accordingly bulk density shows increasing pattern well. The shear strength also increases with depth. These results reflect well the result of dewatering caused by consolidation and/or compaction with sediment depth. The physical properties at two sites show slightly different properties. This may be due to differences of sediment texture, mineralogy, the degree of compaction, and tectonic event in upper plate.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-070

A geodetic study of the southern South Island of New Zealand: Evidence for strain partitioning

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The Pacific Plate in the Southern South Island of New Zealand is characterized by a region of distributed deformation extending from the Alpine Fault to the east coast. This distributed deformation accommodates ~20% of the oblique convergence between the Australian and Pacific Plates. Within this region there are three contrasting styles of deformation with NE striking thrust faults dominating the north-eastern portion, NW striking thrust faults dominating central portion and NE striking thrust faults dominating in the south-west. Upton et al. 2009 described these as the Canterbury, Transitional and Otago Strain Regimes respectively.

We have analysed approximately 20 years of recent satellite-based geodetic data from a broad corridor across the Transitional and Otago regions. Our results support a model of strain partitioning where the Transitional and Otago Strain Regimes are distinguishable by a significant change in the principal axis of contraction from about 80° in the Transitional strain regime to about 120°for the Otago Strain Regime. These principal axes of contraction are roughly orthogonal to the dominant thrust faults in the Otago region but rotated about 40° from orthogonal for the Transitional region. Strain rates range from 70 to 50 ppb for the Transitional and Otago Strain Regimes respectively. Our results support modelling studies of Upton et al. 2009 who predicted a similar change in orientation in the stress field due to the along strike transition from a thin stronger crust in Canterbury Strain Regime and a thicker weaker crust in the Otago Strain Regime.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-071

On the robustness of spectral methods that measure anisotropy in the effective elastic thickness

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Recent studies have inferred patterns of rheological weakness in the lithosphere from analyses of the coherence between gravity and topography data, and related these to tectonic evolution and lithospheric rheology. The methods employed all attempt to estimate the direction of weakest flexural rigidity and the magnitude of the mechanical anisotropy, and their spatial variations whether using the wavelet transform or moving-window multitaper Fourier transform. Here we apply the wavelet transform method to synthetic gravity and topography data derived from plates where the flexural rigidity is known a priori. When analysing plates that replicate the actual topography of North America and Australia, we find that, even when the synthetic plate is isotropic, spurious anisotropy is recovered in which the weak rigidity direction is aligned perpendicular to the strike of major topographic features and continental margins. It appears that strong anisotropy in the gravity and/or topography data is causing the spurious anisotropy in the observed coherence, and that very little artificial anisotropy arises during its inversion. We compare our model weak directions with those from real gravity and topography data over North America and Australia. From synthetic modelling, we also find spurious correlation of the weak rigidity direction with strong gradients in the flexural rigidity. These results suggest that many results of anisotropic spectral analyses of real data should, at best, be treated with caution, and at worst be discarded altogether.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-072

Western Bohemian Massif – seismic anisotropy reveals crust-mantle detachment at Variscan plate boundary

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Bohemian Massif (BM) assembled successively from independent microplates during the Variscan orogeny. While past deformations of the present-day upper crust along paleoplate boundaries are well documented, the way in which the mantle lithosphere deforms during the plate assemblage is not well known. To study the deep fabrics, we model 3D anisotropy of the mantle lithosphere by inverting and interpreting jointly P-wave travel-time deviations and shear-wave splitting parameters of teleseismic waves recorded at portable and permanent stations operating in the BM for more than 20 years. We observe consistent orientation of fossil seismic anisotropy within the mantle-lithosphere domains corresponding to major tectonic units of the BM. Change of this orientation at domain boundaries document rigidity and a long memory of pervasive olivine fabrics.

Lithosphere-scale profiles across the mantle suture between the Saxothuringian (ST) and Teplá-Barrandian (TB) and the mantle boundary between the western rim of the TB and the Moldanubian (MD) reveal shifts around 20 km between the equivalent crustal and mantle boundaries, as well as a detachment of the crust from the mantle lithosphere. Thrusting of the TB mantle lithosphere beneath the margins of the ST and MD crust and the uplifted high-grade metamorphic rocks rimming there the TB crust indicate a Variscan partition of the edge of the TB lithosphere along the base of the crust.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-073

Characteristics of island arc deformation due to steady plate subduction

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Steady plate subduction elastically brings about permanent lithospheric deformation in island arcs. We investigate the characteristics of the permanent lithospheric deformation using a kinematic model, in which steady slip motion is given along a plate interface in the elastic lithosphere overlying the viscoelastic asthenosphere under gravity. As a rule of thumb, long-term lithospheric deformation can be understood as a bending of an elastic plate floating on non-viscous fluid, because the asthenosphere behaves like water in a long term. The steady slip below the lithosphere-asthenosphere boundary does not contribute to long-term lithospheric deformation. Hence, the key parameters that control the lithospheric deformation are only the thickness of lithosphere and the geometry of plate interface. Due to steady slip, gravity causes upward bending for a curved plate interface, while downward bending for a planar plate interface. Larger curvature and thicker lithosphere generally causes faster deformation. When a curvature changes along the plate interface, internal deformation is also involved intrinsically. Because the plate interface generally has some curvature, at least near the trench, upward bending of the island arc lithosphere, which involves uplift of island arc and subsidence around the trench, is always realized. On the other hand, the deformation field sensitively depends on lithospheric thickness and plate interface geometry. These characteristics are consistent with observed topography and gravity anomaly in subduction zones, where a pair of topography and gravity anomaly, high in the arc and low around the trench, exists without exceptions all over the world, while there are large variety in the amplitude and width of the topography and gravity anomaly.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-074

The 2012 Ahar-Varzeghan, Iran, earthquake doublet (Mw 6.4 and 6.2) - rupture kinematics from regional waveforms and InSAR data

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The region of north-western Iran so far was assumed to be tectonically stable with almost no internal deformation, neither in recent nor in historical times. On 11th of August 2012 two earthquakes with magnitudes Mw 6.4 and 6.2 within eleven minutes and only 6km apart in their epicentres disprove this assumption. Because of its particular location between the compressional regime in Iran, the westward extrusion of the Anatolian plate, and the thrusting beneath the Caucasus the earthquake sequence is of special interest for the understanding of the regional tectonics. For the first mainshock - a pure right-lateral strike-slip on a E-W striking subvertical plane - the rupture geometry is evident. However, for the second mainshock - a NE-SW oriented thrust mechanisms - the identification of the rupture plane is ambiguous. A better understanding of the activated faults during the sequence and their interaction would contribute valuable information on the recent tectonics of the region.

We invert regional seismic waveforms for kinematic source parameters and wavefield directivity effects using the code kiwi. The RADARSAT-2 InSAR surface displacement measurements (provided by SOAR2 supported project no. 16736) will contribute further independent estimates on the source orientation and mechanism dislocation. Together with additional information from geology, we present a multi-data analysis of the Ahar sequence.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-075

Mantle dynamics, surface topography and lithospheric stresses since 400 Ma

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We present a model of dynamic topography and lithospheric stresses in a reference linked to the fixed Africa since 400 Ma.
We start with a simple geodynamical model for the large-scale pattern of mantle dynamics in which we combined contributions due to subducted lithosphere and to long wavelength upwellings. We investigated plate motions during the last 400 million years from geological, paleomagnetical and calc-alkaline volcanism data, and assuming that plates have sunk down to the core-mantle boundary, we modeled the temporal evolution of mantle density heterogeneities associated with subductions. From the intraplate volcanism, we identified two broad areas on the Earth surface above the two antipodal domes in the deep mantle, large regions in which material is thermally or compositionally less dense than the surrounding mantle.
Once built this model of temporal variation of the large-scale mantle heterogeneities, we calculate the associated geoid, surface topography and lithospheric stresses and compared them with observations either geodetic or geological:
- The current computed geoid and gravity gradients are in good agreement with satellite observations for large wavelengths.
- Since the Devonian, the comparison of our results with geological surface observations allows us to explain the appearance of some basins in North America (Western Interior Seaway) or Australia (Cretaceous vertical movement) and some expansion areas in Africa (rift).

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-076

"Development of Tibetan crustal structure models from the data of satellite gravity missions"

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We present recent progress in the study of crustal modelling from the data of state-of-the-art satellite gravity missions, which successfully revealed the particular features of the crust-mantle boundary reflecting the compressional tectonic environment. We analysed a multitude of global gravity models up to the year 2014 since 2004. They utilized at least one of the two missions: the Gravity field and Ocean Circulation Explorer (GOCE) and/or the Gravity Recovery And Climate Experiment (GRACE). GOCE, equipped with state-of-the-art gradiometer, was launched by European Space Agency in 2009, and orbits as close to Earth as possible to maximize its sensitivity to variations in Earth's gravity field, while GRACE mission, a joint mission of NASA and the German Aerospace Center, was launched in March 2002 and has two identical spacecrafts flying about 220 km apart in a polar orbit. Formerly Shin et al. (2007, 2009) have revealed three-dimensional models of the Tibetan Mohorovicic discontinuity (Moho and its mountain-ranges-like structure) and its folding structure, on the analogy of lithospheric folding, successfully from the data of GRACE mission. In addition to their models, our recent analysis shows that there are noticeable advances from the GOCE mission than the earlier models, by disclosing the more evident directionality of Moho ranges and folds and by reducing discontinuities of isolated

highs and lows that have been found in the former models.

Reference: [1] Shin, Y. H. et al., 2009, Three-dimensional fold structure of the Tibetan Moho from GRACE gravity data. Geophys. Res. Lett., 36, L01302, doi:10.1029/2008GL036068. [2] Shin, Y. H. et al., 2007, Moho undulations beneath Tibet from GRACE-integrated gravity data. Geophys. J. Intl., 170, 971-985.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-077

Topographic evolution and climate aridification during continental collision: Insights from numerical modeling

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What is the relative importance of tectonics, sediment transport and climate in shaping the topographic evolution of the Earth? During the last three decades, this question has been widely addressed via numerical models constrained with thermochronological and geomorphological data at scales ranging from local to orogenic. Here we present a novel numerical model that aims at reproducing the interaction between those processes at the continental scale. For this purpose, we combine in a single computer program: 1) a thin-sheet viscous model of continental deformation; 2) a stream-power surface transport approach; 3) flexural isostasy allowing for the formation of large sedimentary foreland basins; and 4) an orographic precipitation model that reproduces basic climatic effects such as continentality and rain shadow. We quantify the feedbacks between these processes in a synthetic scenario inspired by the India-Asia collision and the growth of the Tibetan Plateau. We identify a feedback between erosion and crustal thickening leading locally to a <50% increase in deformation rates in places where orographic precipitation is concentrated. This climatically-enhanced deformation takes place preferentially at the upwind flank of the growing plateau, specially at the corners of the indenter. At the continental scale, however, the overall distribution of topographic basins and ranges seems insensitive to climatic factors, despite these do have important, sometimes counterintuitive effects on the amount of sediments trapped within the continent. The dry climatic conditions that naturally develop in the interior of the continent, for example, trigger large intra-continental sediment trapping at basins similar to the Tarim Basin because they determine its endorheic/exorheic drainage.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-078

Contemporary stress and Tectonics in Italy

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The importance of contemporary stress data as input in integrated crustal modeling and as starting point in many applicative researches requires a continuous update of present-day stress maps to get more reliable evaluations. This is particular significant where complex tectonic setting occurs. In Italy, although now the dataset is substantial at large scale, some areas show changes in stress regime over small distances and/or with depth. Thus where information is lacking each prediction of stress patterns could be very different from the reality and then any further evaluation weakly supported by data. We continuously collect stress indicators that become available and here present an update of the last 5 years contemporary stress orientations in Italy. Data are relative to different stress indicators: borehole breakouts from deep wells, crustal earthquake focal mechanisms and fault data. With respect to the previous compilation (Montone et al., 2012) new entries complete the definition of the horizontal stress orientation and tectonic regime in most part of the territory, especially in those regions recently affected by important earthquake sequences as for instance the Emilia 2012 with mainshock M_L=5.9 and the smaller Pollino southern Italy with M_L up to 5.0. All data refer to a depth interval down to 40 km with an assigned quality ranking from A (the best) to E, even though we take into account, at large scale, only A-, B- and C-quality for analyzing main stress patterns and M>4.5 for the earthquakes. In particular in this work we discuss the simultaneous occurrence of different stress regimes and the complex interaction between first order stress field and local effects, and the importance of the inherited tectonic structures on stress field.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-079

Long period GPS data from geodynamic active area in West Bohemia, Czech Republic

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The area around Nový Kostel in West Bohemia, Czech Republic, is well known for its geodynamic activity. The region of Cheb Basin is located at crossing of Eger Rift (ER) and Mariánské Lázne fault (MLFZ) zone.

This paper aggregates results of 20 years of GPS monitoring of the area performed by Institute of Geophysics CAS (IG). The GPS network consists of 26 points. Since July 2006 one GPS permanent station NKIG is operated by IG in Nový Kostel.

Considering the accuracy, the whole area does not show any long term trend displacement within the region. The relative differences in coordinates between "microcampaigns" June 2003 and June 2014 are usually not bigger than 2mm in position and 10mm in height. On the other hand there are several events that can indicate some signal from geotectonic activity in the region. The forward-reverse displacements up to 30 mm in horizontal component during 1998-2000 campaigns. These displacements are consistent with fault plane solution of the Autumn 2000 earthquake swarm. Before the February 2004 micro-swarm we observed an extension of two points near the epicentral zone that was completely eliminated by reverse displacement to previous position in March 2004.

The data from permanent stations NKIG show very good horizontal stability to all reference stations with just few millimeters temporally changes. If we compare sequences of data from periods of main earthquake swarms (Feb. 2007, Oct. 2008, Aug. 2011, Apr. 2013) we have not found yet clear prove of the influence of seismic activity to GPS data.

Unexpectedly, the strongest event since 1985/6 with local M4.4 in 2014 has not produced any significant horizontal pre- or co-seismic displacement according to GPS data.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-080

Rheological structure of the northeastern Japan arc and its viscoelastic deformation after the 2011 Tohoku-oki earthquake

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The northeastern Japan island arc is one of the most favourable locations for studying rheological structures because many types of observational data are available, including seismological, geodetic, and geothermal data, and because significant crustal deformation has been taking place since the 2011 Tohoku-oki earthquake. Dense geothermal observations were conducted using Hi-net boreholes (Matsumoto, 2007) and by Tanaka et al. (2004). We calculate the effective viscosity, considering thermal structure, based on the dense geothermal observations, realistic petrological structures of the upper crust, lower crust, and uppermost mantle. We reproduce several elongated low-viscosity regions, striking transverse to the arc, which correspond to hot fingers.

The viscous relaxation process after the 2011 Tohoku-oki earthquake could have been affected by the existence of low-viscosity regions caused by the hot fingers. A finite element model is developed to investigate the viscoelastic deformation processes after the earthquake, considering the heterogeneous viscosity distribution, and coseismic fault slip distribution (Iinuma et al., 2012). Our numerical results indicate that significant extensional viscous deformation occurs in the low-viscosity regions in the hot fingers. In this case, significant subsidence occurs in the back-arc region and volcanic front, but uplift occurs near the Pacific coast. Also, areal strain decreases with time in the volcanic front. This result is consistent with the observation of a postseismic strain anomaly along the volcanic front after the 2011 Tohoku earthquake (Miura et al., 2014). Our numerical results indicate that the heterogeneous viscosity distribution affects the crustal movements in the inland area significantly.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-081

Ups and downs in Fennoscandia - geodetic strain rates and seismicity influenced by glacial isostatic adjustment

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We derive the surface strain rate field for Fennoscandia from geodetic data and compare it to the deformation at seismogenic depth based on a new compilation of focal mechanisms and historical seismicity. The surface strain rate field clearly shows the effect of the glacial isostatic adjustment (GIA) with a broad signal of NW-SE extension in most of mainland Fennoscandia, surrounded by a radial pattern of shortening. The seismic deformation, on the other hand, mainly shows NW-SE shortening consistent with the mid-Atlantic ridge push, with a tendency towards extension on mainland Fennoscandia. The seismic moment rate is around two orders of magnitudes smaller than the geodetic moment rate. We propose that the reason for the observed discrepancy between surface and depth is, that while the surface deformation is controlled mainly by the present-day GIA, the seismic deformation results from the interaction of the background stress field and flexural stresses caused by both past and present GIA deformation. Our study confirms the notion that the ridge push is the main source of Fennoscandian seismicity, and the influence of GIA on the seismicity is mainly seen as decreased rates and a more mixed seismic deformation field in mainland Fennoscandia. Other sources, such as topography and sediment redistribution, may locally influence the strain rate and stress fields in parts of Norway, which will be the focus of our future investigations.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-082

Estimation of slip deficit by finite element modeling and GPS data inversion in the Longitudinal Valley fault of Taiwan

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The 150 km long Longitudinal Valley fault (LVF) in eastern Taiwan is widely considered as the active collision boundary between the Philippine Sea and Eurasian plates. A high surface velocity gradient of 30– 40 mm/yr was observed across the LVF and the seismicity rate of the LVF is also high. The seismic potential of the LVF depends on the slip deficit accumulated on the fault plane. Thus, it is important to evaluate how the deformation rate observed at the surface is related to the slip on the fault plane. This study uses three-dimensional finite element model (FEM), including surface topography and heterogeneous material property, to compute Green's function for displacement. Then, the observed GPS data will be inversed to evaluate the relative movement on the fault plane. The effects of far field velocity boundary conditions and offshore fault (Taitung trough) shall also be discussed.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-083

Constraints on contemporary tectonic stress regime of Indian subcontinent

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The maximum horizontal stress (SHmax) in the Indian subcontinent observed from the well-breakouts, hydro-fractures and earthquake focal mechanisms vary considerably and are not parallel to the plate velocity direction often. We have made an attempt to simulate orientation and magnitude of SHmax to understand the variability of SHmax. Simulation is accomplished using finite element solver (Abaqus CAE) under plain stress approximation and incorporates heterogeneities in elastic property of Indian continent.

We made simulation for four different scenarios, i) homogenous and ii) heterogeneous plate with fixed boundaries at the north (Himalayan region), and east (Indo-Burmese Arc and Andaman subduction zone; iii) homogeneous and iv) heterogeneous plate with boundary forces applied at the north (Himalayan region), and east (Indo-Burmese Arc and Andaman subduction zone).

We find that estimated orientation and magnitude of SHmax are consistent with observed SHmax for heterogeneous plate with applied boundary forces at the north (Himalayan region), and east (Indo-Burmese Arc and Andaman subduction zone). We also note that variable boundary forces at the northern plate boundary improve the match between observed and simulated SHmax. Thus it appears that boundary condition at northern plate boundary and intraplate heterogeneities play significant role to explain observed intraplate stress field in Indian subcontinent.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-084

Seismic Anisotropy and Surface movement in Northeast Margin of the Tibetan Plateau

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Tibetan Plateau intensely lifts within the Himalayan tectonic evolution. There are lots of large active faults and strong earthquakes in the northeast margin of Tibetan Plateau, where is located in convergence zone among the Tibetan block, Alxa block, Ordos block and South-China block.

In northeastern edge of Tibetan Plateau, the crust movement from GPS data is clearly towards NE and NEE, as well as rotation clockwise. However it is unclear of the deep deformation. We have known that lithospheric deformation and asthenospheric flow, also including typical structure, can lead to observed seismic anisotropy in the upper mantle. Many studies suggest seismic anisotropy is effective to detect the stress, deformation and movement process in the crust and in the mantle. This study adopts shear-wave splitting (SWS) from local events to detect seismic anisotropy in the crust, use splitting of XKS (SKS, PKS and SKKS) phases to detect seismic anisotropy in the lithosphere and asthenosphere, i.e. upper mantle plus crust. GPS data and whole crust anisotropy extracted from receiver functions data are also adopted to analyze surface movement and deep deformation.

Results from SWS in the crust and XKS splitting indicate the anisotropic pattern in the west part in study zone is different to that in the east part. Fast polarizations of SWS in the west part are quite different to that in the east part, which are some related to GPS pattern. The fast direction of XKS shows coherent characteristics between the west part and the east part. We will report these data and analysis in details, with several examples from receiver functions data in the General Assembly of 2015 IUGG.

IASPEI (Seismology, Geophysics)

S08bp - S08b/S08c Lithosphere Structure and Dynamics: Lithospheric Stress and Strain - Observations and Modelling, Plate Boundary Deformation at Lithospheric Scale

S08bp-085

Lithospheric deformation across the margins of the Tibetan plateau: Insights from numerical modeling

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The styles of lithospheric deformation at the margins of the Tibetan Plateau provide clues to how the plateau has grown since the Indian-Eurasian continental collision 65-50 million years ago. Across northeastern Tibet, diffuse lithospheric deformation spreads over a broad zone of different terranes, with gradational topography and Moho depth. In contrast, lithospheric deformation across the eastern Tibetan margin is marked by localized strain, sharp topographic change, and clear off-sets of the Moho. Using a viscoplastic finite element model, we have investigated how rheological variations within the Tibetan lithosphere and between the Tibetan plateau and the bounding blocks may have led to these different styles of lithospheric deformation. Our results show that, when the bounding block is stiff, strain would be localized at the plateau's margin, causing pure-shear thickening of the Tibetan lithosphere, high-angle thrusts in the Tibetan upper crust, and steep topographic gradient. These results are comparable to the eastern margin of the Tibetan plateau. In contrast, when the bounding block is relatively weak, the resulting lithospheric deformation is diffuse over a broad transition zone. With a relatively high plastic strength, the bounding Asian lithosphere is predicted to underthrust beneath the Tibetan Plateau, as suggested by some seismic images in northeastern Tibet.

IASPEI (Seismology, Geophysics)

S09a - S09 Mantle and Core Structure and Dynamics

IUGG-0458

Mapping transition zone thickness under the Paraná Basin of SE Brazil: Evidence for a Mantle Plume?

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The Paraná Basin of SE Brazil is a large cratonic basin of the South American continent that hosts one of the largest Large Igneous Provinces of the planet. An estimated volume of over 2.3x10^6 km^3 of basalt flooded the basin in Cretaceous times, when the Tristan da Cunha plume initiated the opening of the South Atlantic ocean. Interestingly, P- and S-wave tomography imaged a quasi-vertical, low-velocity anomaly in the upper mantle under the basin that resembles the tail of a mantle plume. One interpretation is that the anomaly represents the fossilized tail of the plume that flooded the basin, which would have remained preserved over geologic time as a chemical heterogeneity. A different interpretation, however, sees the anomaly as a modern tail of an unnamed plume that crossed the Amazon basin at 85 Ma. In this work, we investigate the presence or absence of an active upwelling under the Paraná basin by mapping the thickness of the transition zone with receiver functions. The transition zone is bounded by phase transformations in olivine at 410 and 660 km depth that are sensitive to temperature variation. We use a variable bin radius stacking procedure and a background (1D) velocity model to migrate and stack over 1000 low-frequency (fc < 0.24 Hz) receiver functions at 75+ broadband stations in the basin. Our results show that the 410-km discontinuity is depressed about 30-40 km in a small region centered at 19-20 S and 47-48 W, roughly overlapping with the low-velocity anomaly, while the 660-km discontinuity remains flat. Although an expected upwarp of the 660-km discontinuity is not observed, our receiver function stacks reveal a thinning of the transition zone that is consistent with hotter-than-average temperatures and an active upwelling under the basin.

IASPEI (Seismology, Geophysics)

S09a - S09 Mantle and Core Structure and Dynamics

IUGG-1057

The mechanics of intermediate and deep focus earthquakes: experimental evidences

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At least part of the subducting slab seismic activity could be triggered by phase transformations and mineral reactions. However, the way mineral reactions can modify the deformation regime of deep rocks, from ductile to brittle (embrittlement) is still poorly understood and remains one of the outstanding unsolved problems of geophysics and rock mechanics.

Here, we provide the first experimental evidence that, under differential stress at high pressure and temperature conditions, shear fractures nucleate and propagate at the onset of the olivine -> spinel transition in the Mg2GeO4 analogue system. The propagation of these fractures is sufficiently rapid to radiate energy in the form of intense acoustic emissions, which follow the Gutenberg-Richter law over 4 orders of moment magnitudes. Using a similar set-up, a second set of experiments demonstrates that glaucophane, one of the principal mineral water carrier in the subducted oceanic crust, may undergo stick-slip behavior when deformed within the eclogite field (3GPa-500°C), while the quartz-coesite polymorphic transformation (>3GPa, 600°C), a characteristic Ultra High Pressure metamorphic reaction is also shown to be mechanically unstable when performed under stress. Finally, deformation experiments performed on partially serpentinized peridotites demonstrate that 5% serpentine in sufficient to trigger dehydration embrittlement of the peridotite body.

These four observations, when put together, provide experimental evidence which demonstrate beyond reasonable doubt the potential role played by mineral reactions

on earthquake triggering in mantle conditions, both in the Wadati-Benioff double plane of seismicity and the mantle transition zone.

IASPEI (Seismology, Geophysics)

S09a - S09 Mantle and Core Structure and Dynamics

IUGG-1474

Absorption band model for the inner core hemispherical heterogeneity

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We apply a nonlinear waveform inversion method that we developed previously (Iritani et al., 2010, GRL, 2014a PEPI) to broadband (0.02–2 Hz) core phase data recorded by global seismic arrays in order to investigate the frequency dependence of inner core attenuation. The results show a prominent difference of the frequency dependence of attenuation between the eastern hemisphere and the western hemisphere: while attenuation is frequency dependent in the western hemisphere, not so in the eastern hemisphere. Moreover, in the western hemisphere, a stronger frequency dependence of the attenuation is observed beneath Africa compared to beneath North America. This intricate quasi-hemispherical property of the frequency dependence of the inner core attenuation, together with the quasi-hemispherical variability of seismic velocity and attenuation strength at around 1 Hz that we reported earlier, can be consistently understood in terms of the relative location of the seismic observation frequency band and the absorption band peaks that are different for regions (Iritani et al., 2014b, EPSL). This absorption band model for the inner core hemispherical heterogeneity may originate from either the grain size variation, melt fraction variation or variation of other physical properties of the inner core depending on the attenuation mechanism of the inner core which is still poorly understood.

IASPEI (Seismology, Geophysics)

S09a - S09 Mantle and Core Structure and Dynamics

IUGG-1875

Seismic structures in the Earth's mid- and lower mantle

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In recent years, seismology has provided increasingly detailed images of the interior of the Earth, especially since the onset of the deployment of temporary seismic arrays: Seismic tomography has revealed that some slabs descend into the lower mantle while others seem to stagnate at the mantle transition zone; Topography of seismic discontinuities at different depths can provide information the dynamics of the mantle but also on the mineralogy of the Earth's mantle. For example the D' layer has been studied extensively, revealing more and more complex features for which several hypotheses to explain them have been brought forward. Other interesting observations include the topography of the core-mantle boundary, possible detections of upwellings in the deep mantle. In this presentation we will review some of these observations and their connection to dynamics and mineralogy of the Earth's mantle.

We will present detailed images of mantle transition zone structure for several regions, including areas where upwellings are expected, as well as structures that could potentially be direct observations off deep subducted lithosphere. Interpretations of these features can provide valuable information on dynamics and mineralogy of the Earth's mantle.

We will also show results for the D' region (the lowest 200-400 km of the mantle), a region that is often characterized by a reflector. This reflector could be due to the post-perovskite phase transition. However, other possibilities that could cause these structures are deep subducted lithosphere (including MORB) that may be sheared and/or folded, or thermo-chemical layering at the base of the mantle. The different hypotheses will be discussed and their predictions will be compared to seismic observations.

IASPEI (Seismology, Geophysics)

S09a - S09 Mantle and Core Structure and Dynamics

IUGG-3227

Disruption of the PV-PPV phase transition by an upwelling beneath Alaska

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D” represents one of the most dramatic thermal and compositional layers within our planet.In particular global tomographic models display relatively fast patches along the circum-Pacific which is generally attributed to slab-debris.Such cold patches interact with the PV-PPV phase boundary to generate particularly strong heterogeneity at their edges.Most seismic observations for the D” come from the lower mantle S wave triplication (SdS).However the D” region can have a step variation of ~ 100 km beneath the central America which argues for strong lateral temperature variations or possible chemical variations.Here we exploit the USArray waveform data to examine one of these sharp transitions beneath Alaska.From west to east beneath Alaska we observed three different types of D” The Western region with a strong SdS requires a sharp δV_s = 2% increase; Middle region with no clear Scd indicates a lack of D” (no PV-PPV layer).The Eastern region with strong Scd requires a gradient δV_s increase.To explain such strong lateral variation, chemical variations must be involved.We suggest that the Western region represents a normal mantle.In contrast, the eastern region is dominated by the subducted slab.In the Middle region we discovered a strong upwelling structure that disrupts the phase boundary.A distinct pattern of travel time delays, waveform distortions, and amplitude patterns reveal a circular anomaly about 5° across which can be modeled synthetically as a plume-like structure rising about 400km high with a shear velocity reduction of ~ 5%.This up-welling than flattens and rests just above the slab-like structure on the east much like predicted from geodynamic modeling.By adding scatterers in the PPV layer we are also able to explain much of the broad-band waveform features.

IASPEI (Seismology, Geophysics)

S09b - S09 Mantle and Core Structure and Dynamics

IUGG-2175

Seismic Evidence for Ancient Subduction of Izanagi Plate and Dynamic Implication

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Izanagi plate is one of the most important tectonic units shaping the tectonic structure of East Asia from the Creaceous to the Eocene. Disappeared completely from the surface of the earth, it now resides somewhere in the deep mantle. Detecting and mapping the location of ancient subducting slab can assist our understanding of several key problems, e.g. the fate of the subducting lithosphere and the scale of mantle circulation. In this study we undertook a systematic search for deep mantle heterogeneities beneath northeast China and the adjacent Japan Sea through S-to-P converted wave studies. Array stacking techniques were applied to detect the weak signature of the scattered waves indicative of the lower mantle structure. Mid-mantle scatterers within the depth range 930 ~1120 km were revealed to the east of the trapped stagnant Pacific slab, extending ~ 800 km laterally. We argue that the accumulation of MORB-like slab materials at mid-mantle depths causes a different chemical composition than that of the surrounding peridotitic mantle. The spatial isolation of the heterogeneities from the stagnant Pacific slab suggests an origin related to the subduction of ancient Izanagi plate. In combination with the reconstruction history of plate motions, we estimate the viscosity of the topmost lower mantle to vary from $1.0´10^{22}$ to $1.6´10^{23}$ Pa s, which in turn provides an additional constraint for unravelling of the dynamical processes and tectonic history under East Asia up to at least 50 Myr.

IASPEI (Seismology, Geophysics)

S09b - S09 Mantle and Core Structure and Dynamics

IUGG-2621

S-wave velocity structure of the continent of Asia from Rayleigh wave data

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The mantle structure of the continent of Asia was investigated by surface-wave tomography from dispersion of the fundamental mode of the Rayleigh wave group velocities along more than 3200 earthquake-station paths within 30° N to 70° N and 60° E to 150° E. The dispersion curves were processed by a frequency-time analysis procedure at periods from 10 to 250 s. Then group velocity maps were computed separately for each period, at different sampling intervals. We used a tomography method developed for spherical surface. Resolution was estimated according to the effective averaging radius (R) and presented likewise in the form of maps. To estimate the depths of the inhomogeneities, locally averaged dispersion curves were calculated using the group velocity maps, with reference to the radius R, and were then inverted to S-wave velocity-depth profiles. The resulting three-dimensional S-wave velocity structure up to the depths of about 700 km revealed large lateral inhomogeneities through the entire depth range. The inhomogeneities appear as zones of high velocity gradients at boundaries between different tectonic structures or as local velocity maximums and minimums. The most prominent velocity contrasts are concentrated in the upper mantle up to the depths of 400 km. The velocity pattern obtained provides an idea of the lithosphere and asthenosphere thicknesses under different tectonic structures. The distribution of the velocity inhomogeneties may be due to the history of the major tectonic structures, as well as to ongoing processes in the mantle.
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IASPEI (Seismology, Geophysics)

S09b - S09 Mantle and Core Structure and Dynamics

IUGG-3322

Electronic spin and valence states of bridgmanite and post-perovskite in the earth's lower mantle: Implication for the lower-mantle structure

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Bridgmanite is the most abundant mineral phase in the Earth's lower mantle. Based on the pyrolite mantle composition, the volume percentage of bridgmanite is approximately 75%. At pressure-temperature conditions relevant to the lowermost mantle, bridgmanite is expected to undergo the phase transition to Mg-silicate post-pervoskite. Of particular importance is the electronic spin transition of Fe in lower-mantle bridgmanite and post-perovskite which has been shown to affect a number of physical properties, including density, elasticity, and thermal conductivity and provides new insights on the composition and structure of the Earth's lower mantle. Here we will present our most recent experimental results about the spin and valences states of Fe in lower-mantle bridgmanite and post-perovskite using synchrotron M?ssbauer spectroscopy in diamond anvil cells. Our experimental results show that Fe^{2+} and Fe^{3+} in the large pseudo-dodecahedral sites of bridgmanite and post-perovskite stay in the high-spin state at lower-mantle pressures, whereas Fe^{3+} in the smaller octahedral sites can undergo the high-spin to low-spin transition in bridgmanite. With knowledge of the spin and valence states of Fe, we have further studied the equation of state of bridgmanite and post-perovskite with varying Fe and Al content. These new results are used to model the density and velocity of the lower mantle, allowing us to have a better understanding on the compositional variation on the density states and velocity structure of the region.

IASPEI (Seismology, Geophysics)

S09b - S09 Mantle and Core Structure and Dynamics

IUGG-3846

Modelling the thermo-chemical evolution of the mantle starting from a magma ocean

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Several origins have been proposed for compositional heterogeneity in the deep mantle, some of which involve early processes (magma ocean fractional crystallisation, overturn of an early-formed crust, 'upside-down' differentiation) and some of which involve processes occurring over billions of years (segregation of subducted oceanic crust, fractional crystallisation of a basal magma ocean). Perhaps several of these operate, resulting in a heterogeneous Basal Melange (BAM). Magmatic processes (melting, crystallisation) are key in all of these. Indeed, magmatism is one of the most important processes shaping the long-term evolution of our planet. Crust is important for plate tectonics while dense material above the CMB strongly modulates CMB heat flux and the operation and existance of a geodynamo. In a series of papers we have explored several of these issues using simulations of thermochemical convection and differentation over billions of years, but the initial condition for the simulations has always been a solid, compositionally-homogeneous start. Now, however, we have the ability to start the simulations from a molten state (magma ocean), which allows both early and long-term differentiation processes to be included in a self-consistent manner. Our models use an approach previously developed for 1-D magma ocean modelling by Abe, in which dynamics occuring in regions that are mostly solid are fully resolved, while turbulent convection in regions that are mostly molten is parameterised by the use of an effective thermal conductivity. In this presentation, the methodology and motivation will be discussed, together with representative solutions, with a focus on the origin of present-day deep mantle heterogeneity.

IASPEI (Seismology, Geophysics)

S09b - S09 Mantle and Core Structure and Dynamics

IUGG-3919

Evolutionary models of the Earth with a grain size-dependent rheology

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We present a set of numerical simulations of mantle convection in which grain size evolution has a crucial impact on the rheology. We use the thermodynamically consistent models of grain size evolution proposed in the past years [Austin and Evans (2007), Ricard and Bercovici (2009), Rozel et al. (2011), Bercovici and Ricard (2012a,2012b)]. Zener pinning, phase transitions and dynamic recrystallization are incorporated in these very non-linear simulations solved with the convection code StagYY [Hernlund and Tackley (2008)].

Equilibrium situations are presented in 2D spherical annulus models and compared to a grain size-dependent 1D reference profile of the mantle. Our preliminary results have shown that out of equilibrium grain size dynamics leads to localization of deformation below the lithosphere rather than subduction initiation. Yet this result was obtained assuming idealized conditions. We study here, for the first time, the evolution of grain size in the mantle and lithosphere in evolutionary models, from a just-frozen magma ocean until the present day situation. For this purpose, we consider melting, visco-plasticity, phase transitions, compressible convection, and different composite rheologies (diffusion and dislocation creep) in upper and lower mantles.

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IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-593

Small-scale upper mantle convection in the North China Craton and its geodynamic implications

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Small-scale upper mantle convection is one of the main mechanisms to control regional geodynamic processes. The reactivation and destruction of the North China Craton (NCC) are suggested to be related to the small-scale upper mantle convection beneath this area. We present a numerical modeling of the small-scale upper mantle convection beneath the NCC. The instantaneous upper mantle flow is calculated based on density structure inferred from P-wave velocity structure using the finite element method. The results exhibit a very complicated pattern of mantle convection. Mantle downwelling beneath the Ordos Plateau and upwelling beneath its surrounding rifts and Alashan block are found in the western NCC. In the central NCC, the upwelling flow has occurred along the NE-SW direction, which is in good consistent with the regional tectonics. In the eastern NCC, the upper mantle is dominated by the upwelling flow. Across the north-central part of Tanlu fault, however, the flow direction varies dramatically, which changes from upward on the east side to downward on the west side. To investigate the upper mantle deformation mechanisms of the NCC, principal strain rates induced by the predicted upper mantle flow are compared to the observed seismic anisotropy, and the agreement between them is often poor in most area of the NCC, which suggest that the upper mantle anisotropy in the NCC may be caused by the subduction of the Pacific plate beneath the eastern margin of Asia in the east and the India-Eurasia collision in the west, rather than the upper mantle convection at present.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-594

Refraction tomography reveals subduction and exhumation features beneath the high-grade terrains in the Eastern Bohemian Massif

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Two high-grade belts in the Eastern Bohemian Massif are assumed the result of deep exhumation processes following the Moldanubian boundaries with the surrounding Teplá-Barrandian and Moravo-Silesian units. The seismic SUDETES 2003 and CELEBRATION 2000 experiments provided refraction data along four profiles mapping this area. The applied depth-recursive tomography succeeded in resolving the features due to the exhumation of coupled low-velocity (LV) felsic and high-velocity mafic rocks. The enhanced P-wave velocity sections along the S02, S03, S04 and CEL09 profiles coherently image the assumed exhumation and preceding subduction processes.
Along the eastern belt, the S03 image resolved two diapiric LV bodies located beneath the gneiss Orlica-Snieznik Dome and Gory Sowie Unit. The LV diapiric bodies obviously correspond to the felsic gneisses that ascended from the mantle to supracrustal levels. The former LV anomaly extends into shallow depths, which indicates a common source of HP-UHP rocks in the eastern belt. Along the western belt, the S02 and S04 sections imaged an extended HV body shallowly emplaced beneath the Gföhl and Ostrong terranes. The S02 section indicates its autochthonous nature due to its mid-crust sources represented as HV diapiric anomalies that interlay LV diapiric ascents.
The observed felsic exhumations are always coupled with HV sub-vertical anomalies indicating the concurrent ascents of juvenile mafic magmas. Moreover, we always observed shallow mafic emplacements that intercalate the felsic diapiric ascents. The different rheology of felsic and mafic melts and a longer persisting ascent of mafic magmas may explain these phenomena.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-595

Can we explain the D" reflector with the post-perovskite phase transition?

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Seismic observations from the lower Earth's mantle indicate a reflector that marks the top of the D' region. Many studies have imaged this reflector in previous years, many of them in high-velocity regions that could be due to slab graveyards, and many interpretations have been published previously. Since the discovery of the post-perovskite phase transition ten years ago, the D' reflector has often been interpreted as the place of the phase transition. Even looking at wave forms, polarities, deeper reflectors and amplitudes of the reflected waves has shown agreement with properties of post-perovskite and the confidence of it as the cause for the D' reflector has been increasing. Here we are looking at several new places and identify D' reflections in P and S-waves: we target especially low velocity regions and places, where we do not expect slab material in the lowermost mantle. We test wave forms, polarities, amplitudes, timing and frequency content of the reflected waves and compare these across many diverse regions in the mantle. It seems that post-perovskite can still explain many observations; however, a large number of assumptions has to be made to explain all observations in all regions simultaneously and leaves the question whether the reflector in D' can always be explained through a phase transition to post-perovskite or whether we have to consider other possibilities.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-596

Is there any correlation between continents and elevated temperatures in the subcontinental mantle?

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Rolf et al. (EPSL, 2012) and Coltice et al. (Science, 2012) have previously shown that continents exert a first order influence on Earth's mantle flow by affecting convective wavelength and surface heat flow. However, how continents influence the development and location of mantle plumes remains a topic of considerable debate.

Continental motion is attributed to the viscous stresses imparted by the convecting mantle and the extent of this motion depends on the heat budget of the mantle. Core-mantle boundary (CMB) heat flux, internal heating from decay of radioactive elements, and mantle cooling contribute to this heat budget. Out of these sources, CMB heat flux is not well defined. However, the recent determination of core's high thermal conductivity requires a CMB heat flow of at least 12 TW (de Koker et al., PNAS 2012; Pozzo et al., Nature 2012; Gomi et al., PEPI 2013). Thus it is necessary to characterize the impact of basal heating on mantle dynamics with continents and self-consistent plate tectonics.

By systematically varying parameters like CMB temperature, continental size, mantle heating modes (basal and internal), and Rayleigh number; we model Boussinesq, incompressible, thermo-chemical mantle convection using StagYY (Tackley, PEPI 2008). We observe correlation between continents and elevated temperatures in the subcontinental mantle irrespective of the variations in basal heating and continental size (except for very small continents). Moreover, we see episodicity between correlation and anti-correlation with increasing Rayleigh number. Furthermore, the effect of radioactivity in the continental crust on this correlation is investigated. We will also show first results for continental growth as opposed to having prescribed continents in StagYY.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-597

Early evolution and dynamics of Earth from a molten initial stage

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Most of the terrestrial planets underwent a magma ocean stage during their evolution. On Earth, it is probable that at the end of accretion, giant impacts like the Moon-forming impact, together with other sources of heat, melted a substantial part of the mantle. Considerable research has been done on magma oceans using simple 1-D models (e.g.: Abe, PEPI 1997; Solomatov, Treat. Geophys. 2007; Elkins-Tanton, EPSL 2008). However, some aspects of the dynamics may not be adequately addressed in 1-D and require the use of 2-D or 3-D models.

The goal of our study is to understand the influence of melting on the long-term thermo-chemical evolution of rocky planet interiors, starting from an initial molten state. Our approach is to model viscous creep of the solid mantle, while parameterizing processes that involve melt as previously done in 1-D models, including melt-solid separation at all melt fractions, the use of an effective diffusivity to parameterize turbulent mixing, coupling to a parameterized core heat balance and a radiative surface boundary condition. These enhancements were made to the numerical code StagYY (Tackley, PEPI 2008).

We will present results for the evolution of an Earth-like planet from a molten initial state to present day, while testing the effect of uncertainties in parameters such as melt-solid density differences, surface heat loss and efficiency of turbulent mixing. Our results show rapid cooling and crystallization until the rheological transition then much slower crystallization, large-scale overturn well before full solidification, the formation and subduction of an early crust while a partially-molten upper mantle is still present, transitioning to mostly-solid-state long-term mantle convection and plate tectonics or an episodic-lid regime.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-598

Role of viscoelasticity in mantle convection models

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A present limitation of global thermo-chemical convection models is that they assume a purely viscous or visco-plastic flow law for solid rock, i.e. elasticity is ignored. This may not be a good assumption in the cold, outer boundary layer known as the lithosphere, where elastic deformation may be important.

A method for adding elasticity to a viscous flow solver to make a visco-elastic flow solver, which involves adding advected elastic stress to the momentum equation and introducing an 'effective' viscosity has been proposed (e.g. Moresi, 2002). In this study we test a grid-based version of the method in context of thermal convection in the Boussinesq approximation.

The main obstacle is that Maxwell viscoelastic rheology produces instantaneous deformation if instantaneous change of the driving forces occurs. It is not possible to model such deformation in a velocity formulated convection model, as velocity undergoes a singularity for an instantaneous deformation. For a given Rayleigh number there exists a certain critical value of the Deborah number above which it is necessary to use a thermal time step different from the one used in viscoelastic constitutive equation to avoid this numerical instability from happening. Critical Deborah numbers for various Rayleigh numbers are computed. We then propose a method to decouple the thermal and constitutive equations in a way more suitable for global studies, which is different from the method refered to earlier. The computational domain is expected to be composed of two parts: One in which elastic effects are important and where material does not move significantly within one elastic time step and one where elastic effects are not important, where material is allowed to move across many cells within one elastic time step.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-599

P-wave velocity anomalies of the plume beneath the French Polynesia

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The French Polynesian region is characterized by positive topographic anomalies of 700 m, a concentration of hotspot chains. A new P-wave tomography with better resolution in the upper mantle was obtained by using data from the French Polynesian island stations and broadband ocean bottom seismometers around the reagion and by taking the finite frequency effect into account for the frequency-depended differential travel times. The frequency-depended differential travel times were measured by multi-band cross correlating P waveforms. The result shows strong low-velocity anomalies beneath the Society Islands and Pitcairn in the upper mantle although they do not extend to the 660-km discontinuity. This model also shows that small-scale low-velocity anomalies in the uppermost lower mantle. The low-velocity anomalies in the depth range about 550 - 900 km are smaller both in lateral area and amplitude than those in most of the upper mantle and the lower mantle. The velocity patterns are well correlated each other in the depth range but are not correlated with the patterns above and below, indicating the mantle beneath the French Polynesia can be divided into 3 layers in terns of radial correlation.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-600

Scaling laws for the internal temperature reached in the stagnant lid regime with depth-dependent non-Newtonian rheologies

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We present an analytical scaling law for the internal temperature reached at the equilibrium of mantle con- vection simulations in the stagnant lid regime. The depth-dependence of the viscosity is explicitly incorporated in the boundary layer theory applied to non-Newtonian rheology and it is found to have a very strong influence on the internal temperature, which controls the Rayleigh number and the lithosphere stresses.

A large set of numerical simulation results of mantle convection is then presented. Internal temperatures are collected in all cases: Newtonian or non-Newtonian, stationary or not, in Arrhenius or Frank-Kamenetskii approximations, cartesian or spherical geometries, etc. We use this large dataset to test the validity of the prediction for the equilibrium internal temperature, iteratively looking for the parameters that best fit the data. The best fitted parameters converge very close to the analytical prediction, which fully confirms it. Although our new analytical model only concerns the internal temperature, we discuss its strong implicit impact on the heat flux.

Finally, we present an additional set of simulations in which time-dependent internal heating and evolving core temperature keep the internal temperature out of equilibrium. We also show that the effective Rayleigh number controls the equilibration time of the internal region. The effect of melting on the internal temperature is also discussed.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-601

Stagnant Honshu slab and its implication for Japan Sea Opening and off-arc volcanism

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We obtained a three-dimensional P-wave velocity model with focus on the northwestern Pacific using P data from a temporal seismic array deployed in the Northeast China with global data. Differential travel times between any two stations as a function of frequency are inverted by taking finite frequency effect into account to improve resolution through the upper mantle. The obtained subducted slabs of > 0.5% fast anomalies are different from that of > 1.0% anomalies in the mantle transition zone. The former shows simple and lataeraly extended aomalies of which western boundary is linear and probably is parallel to the Paleo-Pacfic sunduction zone. The latter shows complicate cinfiguration. The results also show slow anomalies below the Late Cenozoic volcanoes in Northeast China down to about 200 km depth except for the Changbaishan volcano where the slow anomaly down to further depths is observed. The results also show a fast anomaly from surface to the about 250 km depth and absence of stagnant Honshu slab in the mantle transition zone in contrast below Songliao basin. The authors speculate that the slab gap in the mantletransition zone is realated to the Inception of Japan Sea Opening and Northeast China Cenozoic volcanoes.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-602

Crustal anisotropy beneath the western segment of north anatolian fault zone

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Shear-wave splitting from local earthquakes provides valuable knowledge on anisotropy of the upper crust.North Anatolian Fault Zone is a large-scale continental strike slip fault system originating at the Karliova Junction in the east where it intersects the East Anatolian Fault and extends west cut-ting across the entire Northern Turkey towards the Aegean Sea and the mainland Greece . Our primary focus is to provide constraints on the crustal anisotropy beneath the western segment of the North Anatolian Fault Zone with the use of a data set collected from a dense temporary seismic network consisting of 70 stations that was deployed in early May 2012 and operated for 18 months in the Sakarya region and the surroundings during the Faultlab experiment. For the local shear wave splitting analysis, out of 1371 events, we extracted 90 well located earthquakes with magnitudes greater than 2.0. Incidence angles of less than 45 degrees were used to avoid the free-surface effect and resulting non-linear particle motion. Basically, two essential parameters for each station-event pair is needed for shear wave splitting calculations. One of them is fast polarization direction (?) and the other is delay time (δt) between the fast and slow components of the shear wave. In this study, delay times vary between 0,02 and 0,25 seconds clearly reveals the existence of crustal anisotropy. We are also going to attempt to correlate the fast directions obtained for the group of stations with the tectonic regime of the region taking into account these parameters.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-603

Linking the dynamics and evolution of lower mantle heterogeneities with surface plate motions

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Numerical studies of mantle convection have attempted to explain tomographic observations that reveal a lower mantle dominated by broad regional areas of lower-than-average shear-wave speeds beneath Africa and the Central Pacific. Termed LLSVPs (“large low shear velocity provinces”), the anomalous regions are often inferred to be thermochemical structures encircled by regions of higher-than-average shear-wave speeds associated with Mesozoic and Cenozoic subduction zones. The origin and long-term evolution of the anomalous regions remains enigmatic. It has been proposed that the LLSVP beneath Africa was not present before 200 Ma, prior to which time the lower mantle was dominated by a degree-1 convection pattern with a major upwelling centred close to the present-day Pacific LLSVP and subduction concentrated mainly in the antipodal hemisphere. The African LLSVP would thus have formed during the time-frame of the supercontinent Pangea as a result of return flow in the mantle due to circum-Pacific subduction. We present results from a geodynamic-seismology study that investigates the hypothesis that the Pacific LLSVP is indeed much older than its antipodal counterpart by performing 3D numerical models of mantle convection integrated with a new plate tectonic history model. We improve upon previous studies by imposing kinematic surface velocity boundary conditions for a time interval that spans the amalgamation and subsequent break-up of Pangea and by allowing for a lateral heterogeneity difference between the African and the Pacific LLSVPs.

IASPEI (Seismology, Geophysics)

S09p - S09 Mantle and Core Structure and Dynamics

S09p-604

Mobilizing a very high viscosity lower mantle

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Two dimensional numerical models of mantle convection in a cylindrical shell are employed to investigate the impact of the very high viscosities in the lower mantle as proposed by Mitrovica and Forte (2004). Models are considered with and without mineral phase transitions. Our viscosity profiles are depth dependent with lower mantle viscosities increasing with depth to values of 300 times the viscosity of the upper mantle and then decreasing dramatically on approaching the core-mantle boundary. Although phase transitions produce small secondary effects on the flow structure, the main effect is that of the viscosity decrease near the core mantle boundary. Models with a high viscosity structure extending down to the core-mantle boundary are very sluggish with large aspect ratios, whereas models with a low viscosity just above the core mantle boundary overturn rapidly with aspect ratios close to unity. The latter models resemble uniformly low viscosity models despite the high viscosity region at mid-depths of the lower mantle.

IASPEI (Seismology, Geophysics)

S10a - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-0871

Operational earthquake forecasting in the Eastern Caribbean

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Earthquake forecasting and, eventually, prediction is one goal of seismological research. As we cannot predict the exact date, time, magnitude and location of the next damaging earthquake, scientists seek patterns that appear precursory to the occurrence of damaging earthquakes for operational forecasting or alerts. In the Eastern Caribbean, it has been observed that earthquakes in the magnitude range 7.0-7.9 occur about once every 20-30 years on average, and those of magnitude 8 and larger, have average return intervals of 100 or so years. These observations have been, and are being, used to promote the desirability and benefits of having some earthquake preparedness measures in place. On shorter time scales, the piecewise Gutenberg-Richter b-value gradient-tracking technique can sometimes provide an indication of the possible imminence of a moderate to strong earthquake, with some potential to cause damage or casualties. Insights from Operational Volcanic Forecasting, implemented successfully several times with volcanic unrest and eruptions in the Eastern Caribbean, since the 1960's, are being applied to situations with locally anomalous earthquake activity. Disaster coordinators are apprised of such signs, the status of activity and our prognosis, which allow them an opportunity to tailor timely and appropriate response measures. On the basis of contemporary deviations from linearity in the piece-wise Gutenberg-Richter data, Antigua and Saint Lucia are two such zones that currently are in 'watch' status. Tobago is also in 'watch' status based on an association of earthquakes in that zone with those in the Vema Fracture Zone.

IASPEI (Seismology, Geophysics)

S10a - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-2281

Operational Earthquake Forecasting: a New Zealand Perspective

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Recent earthquakes in New Zealand in the last few years have provided significant experience in aftershock hazard and forecasting. The Canterbury sequence, including the destructive Christchurch earthquake of February 2011, is occurring in what was a moderate-to-low hazard region of the National Seismic Hazard Model. With the expectation that the sequence would produce hazard in exceedance of the existing building standard, we developed a time-dependent model that combined short-term and medium-term clustering with time-independent models to produce a forecast of the hazard for the next 50 years. This model has been used to revise building design standards for the region and has contributed to the planning of the rebuilding of Christchurch in multiple aspects. An important contribution to this model comes from the inclusion of the EEPAS model, which allows for clustering on the scale of decades. A second important contribution comes from the long-term rate to which seismicity is expected to return in 50-years.
With four additional moderate sequences in the last year, we have continued to refine our forecasting techniques through better understanding of the relevance of forecasting time-windows, data quality issues, better use of social science and by incorporating scenarios developed from the aftershock forecasts. These earthquake scenarios provide examples of how the sequence might develop, including the understanding of nearby faults and the Hikurangi megathrust. They have been developed with input from social scientists and communication specialists. They have been provided to the public and government officials and have proven useful in aiding the interpretation of the aftershock probabilities.

IASPEI (Seismology, Geophysics)

S10a - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-3168

Long lasting practice and objectivist vision of Operational Earthquake Forecasting (OEF)

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By 1980ies seismically active lithosphere of the Earth has been recognized as a complex hierarchically self-organized nonlinear dissipative system with critical phase transitions through larger earthquakes. Such “chaotic” systems are predictable, but up to a limit and after substantial averaging. Accordingly, a success in forecasting earthquakes implies a holistic approach and OEF is posed as a successive, step-by-step, narrowing the magnitude range, territory, and time of expectation. An objectivist understanding of earthquake prediction problem is naturally expressed in empirical mathematically routed models. Since 1980ies forecasting tools are subject to rigid testing in retrospect, then in real-time so that to judge the ultimate success or failure of the effort. It is undebatable that only careful record of failures and successes can eventually evaluate reliability and effectiveness of forecasting. A reliable confidence level assigned to prediction arises from an objective score achieved in a durable real-time testing (experiment concept) and by no means from ad hoc subjective hypothesizing (probability concept). Reasonable confidence limits on recurrence rate of earthquakes require geologic time-span which is unreachable for historical seismology. Earthquake prediction makes use of seismic clustering observed through magnitude-space-time scales and can provide to decision-makers reliable forecasting information for implementation of the full broad spectrum of possible actions. Prudent cost-effective safety measures can be taken if prediction certainty is known, but not necessarily high. Communicating

OEF and its uncertainties must be done with a keen feeling of responsibility for the final outcome in warning people of looming disaster.

IASPEI (Seismology, Geophysics)

S10a - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-3803

Operational earthquake forecasting of aftershocks for new England, USA

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Although the forecasting of mainshocks is not possible, recent research demonstrates that probabilistic forecasts of expected aftershock activity following moderate and strong earthquakes is possible. Previous work has shown that aftershock sequences in intraplate regions behave similarly to those in California, and thus the operational aftershocks forecasting methods that are currently employed in California can be adopted for use in areas of the eastern U.S. such as New England. In our application, immediately after an earthquake of magnitude 4.0 or greater, a forecast of expected aftershock activity for the next 7 days will be generated based on a generic aftershock activity model. Approximately 24 hours after the mainshock, the parameters of the aftershock model will be updated using the observed aftershock activity observed to that point in time, and a new forecast of expected aftershock activity for the next 7 days will be issued. The forecast will estimate the average number of weak, felt aftershocks and the average expected number of aftershocks above magnitude 4.0. The forecast also will estimate the probability that an earthquake that is stronger than the mainshock will take place during the next 7 days. The aftershock forecast will specify the expected aftershocks locations as well as the areas over which aftershocks of different magnitudes could be felt. The system will use web pages, email and text messages to distribute the aftershock forecasts. For protracted aftershock sequences, new forecasts will be issued on a weekly basis. Initially, the distribution system of the aftershock forecasts will be limited, but later it will be expanded as experience with and confidence in the system grows.

IASPEI (Seismology, Geophysics)

S10a - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-3886

Scientific and non-scientific challenges for operational earthquake forecasting

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Tracking the time evolution of seismic hazard in time windows shorter than the usual 50-years of the long term hazard models may offer additional opportunities to reduce the seismic risk. This is the target of operational earthquake forecasting (OEF) that has been recently proposed by the International Commission for Earthquake Forecasting nominated after L'Aquila earthquake in 2009.
OEF implementation has several challenges that range from pure Science to the more practical interface of Science with society. Interestingly, facing this wide range of challenges calls for a much better definition of the still fuzzy boundaries among the different competences required for the whole risk mitigation process. From a scientific point of view, it is essential to evaluate the reliability and skill of earthquake forecasting models in different time windows. Presently the most reliable models are based on earthquake space-time clustering but their skill is rather limited; it is indispensable to evaluate if accounting for different physical and/or geological components may increase the forecasting skill. Besides the scientific aspects, there are other very important non-scientific challenges that have to be tackled. For instance, OEF usually provides large earthquake probabilities smaller than 1%; in this case, it is crucial to define a proper messaging to a wide range of potential stakeholders, because a wrong message could be useless or even counterproductive.
The aim of this talk is to discuss in detail all these issues.

IASPEI (Seismology, Geophysics)

S10a - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-5485

Operational earthquake forecasting from significant seismicity changes in Greece

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The region of Greece and surrounding areas is characterized by the highest seismicity in the western Eurasia. As an average at least one earthquake of magnitude 6 or larger takes place annually. The 24/7 seismicity monitoring of the country under the coordination of the Institute of Geodynamics, National Observatory of Athens (NOAGI) provides automatic and manual solutions of seismic events of magnitude as low as about 1.5, which provides earthquake catalogues updated as soon as an earthquake occurs. Time-dependent seismic hazard assessment is performed on the basis of statistically significant changes of seismicity in a nearly real-time frame (time delay of 24 hours from the activity under examination). Background seismicity is the reference model under the assumption that in a target area no changes in the seismicity rate, r, and in the G-R b-value are concurrent at significance level exceeding 0.95. When significant changes of r and b are concurrent, then a clustering style of seismicity deviating from background is investigated based on a formalism developed with the adoption of results published by a long number of authors globally: r and b increase indicates swarm; r increase and b decrease indicates foreshock activity; r and b increase after a strong earthquake indicates aftershock activity. Good examples from Greece, Italy, Southern California and Japan are demonstrated. When such significant changes are detected messages are circulated internally in NOAGI and forwarded to national agencies charged with the antiseismic policy of the country. The software in use is FORMA (Foreshocks-Mainshock-Aftershock) which was developed by our team in a platform of C++ for the needs of this application. This is a contribution to the internal NOAGI project EARTHWARN.

IASPEI (Seismology, Geophysics)

S10b - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-1766

How to combine rate-based earthquake forecasting models with precursory information or with non-normalized models?

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During last years a significant progress in developing and testing earthquake forecasting models was demonstrated, especially due to the activity of the Collaboratory for the Study of Earthquake Predictability (SCEP). Large number of forecasting models have been installed for testing in SCEP centers, most of them forecasting earthquakes rates in various time scales (from days to years). The models demonstrating the best accordance with reality are based on spatial and/or temporal clustering of seismicity. Those models, however, deal with very low probabilities, or expected rates, of large earthquakes, the only exception is short-term forecasting right after largest earthquakes. The expected rates could be increased prior to earthquakes by incorporating into the models precursory phenomena, for example earthquake swarms. The methods developed to combine several rate-based forecasting models are not adapted to combine models with precursory information or with non-normalized models including alarm-based ones. We propose a method to combine earthquake forecast rate-based models with any information that could locally increase the forecasted earthquake rates. We use the differential probability gain calculated in the Molchan diagram that evaluates the performance of the input information with respect to the rate-based model. Then, at each point in space and time, the new rate is the product of the current rate times the local differential probability gain. The main advantage of our combining method is its capacity to produce high expected event rates. We demonstrate how the method works on several examples. The research was partially supported by Russian Foundation of Basic Research (Project N 13-05-00541).

IASPEI (Seismology, Geophysics)

S10b - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-3071

UCERF3-ETAS: Including Spatiotemporal clustering for a California Operational Earthquake Forecast

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The Working Group on California Earthquake Probabilities (WGCEP) has been developing the third Uniform California Earthquake Rupture Forecast (UCERF3). With the long-term, time-dependent model published, which relaxes segmentation, includes multi-fault ruptures, and incorporates elastic rebound, we have now turned our attention to including spatiotemporal clustering. Recongnizing that triggered events can be large and damaging, the ultimate goal is to deploy an Operational Earthquake Forecast (OEF) for California, now listed as one of the USGS's strategic-action priorities (http://pubs.usgs.gov/of/2012/1088; page 32). This presentation will demonstrate progress thus far, wherein we have added an Epidemic Type Aftershock Sequence (ETAS) component to UCERF3 (UCERF3-ETAS). Notably, our model represents a merging of ETAS with finite-fault based forecasts, as well as the inclusion of elastic rebound (both firsts, as far as we are aware). In fact, inclusion of elastic-rebound turns out to be critical in terms of replicating spatiotemporal clustering statistics (otherwise ~85% of large triggered events re-rupture the same fault, which we don't see in nature). This presentation will also outline efficient loss calculations and additional steps needed for taking UCERF3-ETAS operational.

IASPEI (Seismology, Geophysics)

S10b - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-3493

Operational earthquake forecasting in California: A prototype system combining UCERF3 and CyberShake

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Operational earthquake forecasting (OEF) is the dissemination of authoritative information about time-dependent earthquake probabilities to help communities prepare for potentially destructive earthquakes. The goal of OEF is to inform the decisions that people and organizations must continually make to mitigate seismic risk and prepare for potentially destructive earthquakes on time scales from days to decades. To attain this goal, OEF must provide a complete description of the seismic hazard—ground motion exceedance probabilities as well as short-term rupture probabilities—in concert with the long-term forecasts of probabilistic seismic hazard analysis. We have combined the Third Uniform California Earthquake Rupture Forecast (UCERF3) of the Working Group on California Earthquake Probabilities (Field et al., 2014) with the CyberShake ground-motion model of the Southern California Earthquake Center (Graves et al., 2011) into a prototype OEF system for generating time-dependent hazard maps. UCERF3 represents future earthquake activity in terms of fault-rupture probabilities, incorporating both Reid-type renewal models and Omori-type clustering models. The current CyberShake model comprises approximately 415,000 earthquake rupture variations to represent the conditional probability of future shaking at 285 geographic sites in the Los Angeles region (~236 million horizontal-component seismograms). This combination provides significant probability gains relative to OEF models based on empirical ground-motion prediction equations (GMPEs), primarily because the physics-based CyberShake simulations account for the rupture directivity, basin effects, and directivity-basin coupling that are not represented by the GMPEs.

IASPEI (Seismology, Geophysics)

S10b - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-4989

Exploring the reliability of ETAS earthquake forecasts as a function of the model parametrization

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Traditionally, seismic risk reduction is achieved only through a sound earth- quake building code. Nonetheless, some recent seismic disasters have highlighted the need for enlarging the range of risk mitigation actions beyond that. In particular, short-term earthquake forecast offers additional information that may increase vigilance and preparedness in a short-time frame. To date, one of the most reliable models for short-term earthquake forecasts is the epidemic-type aftershock sequence (ETAS) model. Although ETAS has been originally proposed to track the evolution of a seismic sequence after a large event, more recent analyses underline the ETAS capability to describe the evolution of any seismic sequence. In this work we analyze the performance of different ETAS configurations applied to two Italian seismic sequences (Aquila 2009 and Emilia 2012), in order to understand which parameters of the model are the most important to provide reliable forecasts. Among other parameters, we explore the influence of the completeness magnitude of the input catalog and the effects of its time variability after large earthquakes.

IASPEI (Seismology, Geophysics)

S10b - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-5048

How do you know if the background seismicity rate has changed?

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Operational earthquake forecasting requires continuously-updated seismicity models which combine a random background rate with a conditional probability of triggering subsequent events. During an aftershock sequence relatively high and robust probability gains can be obtained, but how good are our algorithms at detecting changes in background rate? First we examine the significance of the rate change for the Umbria-Marche region of Italy during a strong sequence of earthquakes in 1997-8. We apply a maximum-likelihood (ML) inversion of the epidemic-type aftershock sequences model to characterize the seismicity of this region over 22 years. We confirm the event rate during the sequence is under-predicted by a stationary ML solution, with the large M≥5 events fixed. However, by sampling the parameter space around the ML solution within the inversion uncertainty, and adding the constraint that the average event rate for the model must match that of the data, we obtain an alternative stationary solution that matches the data better than the ML fit. We then use simulation experiments to test the effectiveness of various statistical methods for inferring a change in background rate, including calculation of the Bayes factor as a model discriminant. We show that is important to include as many smaller events as possible when de-clustering earthquake data - to more fully remove aftershocks. We find no strong evidence that the background rate of large events worldwide has increased in recent years.

IASPEI (Seismology, Geophysics)

S10b - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-5398

Retrospective evaluation of time-dependent earthquake forecast models during the 2010-12 Canterbury, New Zealand, earthquake sequence

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With efforts underway in New Zealand, Italy and the US to deploy Operational Earthquake Forecasting (OEF) systems, an objective evaluation of the predictive skills of candidate OEF models is crucial for transparent model choices and the credibility of disseminated information. For this purpose, the Collaboratory for the Study of Earthquake Predictability (CSEP) is conducting a retrospective evaluation of time-dependent forecast models during the complex and fatal 2010-12 Canterbury, New Zealand, earthquake cascade. Fourteen models were developed by groups in New Zealand, Europe and the US, including statistical, physics-based and hybrid models. We evaluated the models from the time just after the Mw7.1 Darfield earthquake until February 2012 using three forecast durations (1-year, 1-month and 1-day). In stark contrast to previous comparisons between Coulomb stress models and statistical models, the information content of physical and hybrid model forecasts is greater than or comparable to that of statistical model forecasts at all forecast horizons. Differences are greatest for 1-yr horizons, where variants of the Coulomb model and a hybrid model outperform a reference ETAS model by a probability gain per earthquake of about 7. The influence of near-real-time data on forecast skill is complex and model-dependent: the effect varies from insignificant to substantial but does not necessarily degrade quality. Our results offer some

encouragement for a physical basis in OEF and suggest that some of the recent physics-based and hybrid model development has added informative components.

IASPEI (Seismology, Geophysics)

S10c - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-1878

Randomness of mega-thrust earthquakes implied by rapid stress recovery after the Japan M9 event

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Constraining the recurrence of mega-thrust earthquakes is genuinely important for hazard assessment and mitigation. The prevailing approach to model such events relies on subduction zone segmentation and quasi-periodic recurrence due to constant tectonic loading. Here we analyze earthquakes recorded along a 1,000-km-long section of the subducting Pacific Plate beneath Japan since 1998. We find that the relative frequency of small to large events varies spatially, closely mirroring the large-scale tectonic regimes, and suggesting a laterally unsegmented mega-thrust interface. Starting some years before it broke, the Tohoku source region is imaged as a region of high stress concentration. Following the 2011 M9 earthquake, the size distribution changes significantly and most dramatic in the areas of highest slip. However, we discover that it returns within just a few years to its longer-term characteristics as observed prior to the mega-thrust event. This indicates a rapid recovery of stress and implies that such large earthquakes may not have a characteristic location, size or recurrence interval, and might therefore occur more randomly distributed in time.

IASPEI (Seismology, Geophysics)

S10c - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-2687

The EEPAS forecasting model ten years on

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The EEPAS (Every Earthquake a Precursor According to Scale) model is an earthquake forecasting model based on the precursory scale increase phenomenon – an increase in the magnitude and rate of occurrence of minor earthquakes observed to occur in the medium term before most major earthquakes in well-cataloged regions. First published in 2004, the model adopts the predictive relations for time, magnitude and area that were first noticed by F. Evison in 1976 in relation to precursory swarms. Setting aside the question of recognizing precursory sequences, it applies the predictive relations to all earthquakes, although aftershocks are down-weighted in the formulation that works best at high magnitudes. We review its development, testing and varied application over a decade. It has been fitted and tested on numerous regional catalogs and a global catalog. Although initially intended for forecasting large earthquakes, it has consistently outperformed smoothed seismicity models with a range of magnitude thresholds and in a variety of tectonic environments. It has been tested by the Collaboratory for the Study of Earthquake Predictability (CSEP) in several regions. It has been used, and shown to be informative, in hybrids with short-term forecasting models. It has been applied as a component of operational earthquake forecasts in New Zealand. It has given good precursory indications of the magnitude and location of several major earthquakes in recent years, with an exception being the Canterbury earthquakes. It has been found to fit well to synthetic earthquake catalogs generated by two physics-based earthquake simulators. The latter application indicates how the precursor time should vary with the strain rate - a question that is relevant to the Canterbury earthquakes.

IASPEI (Seismology, Geophysics)

S10c - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-3747

The medium-term seismic hazard model for Italy

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The INGV Seismic Hazard Center (Centro di Pericolosità Sismica – CPS) is in charge to develop a model for the quantification of the medium-term seismic hazard, which has important social applications and a wide range of potentially interested stakeholders. The medium-term models fill the gap between the two extremes represented by the short-term hazard and the long-term one. While the former one is characterized by Omori-Ustu cluster occurrence and has a forecasting time window of a few days / weeks, the latter one is mainly based on time-independent processes with a time window of forecast of tens of years. The medium-term models are the transition between these two time intervals with time windows ranging from a few months (e.g., six months) to a few years (e.g., 5 years).

Our strategy consists in the weighting different hazard models in order to create an ensemble model, with the aim to describe the aleatory variability and the epistemic uncertainty in a consistent way. We merge different models of earthquake rate and Ground Motion Prediction Equations (GMPEs) and we discuss some examples showing the forecasting performances of the ensemble model with respect to each single model.

For the earthquake rate, at this early stage, we rely exclusively on models subjected to EU CSEP Testing Center. The choice to use only these models is motivated by the need to have models already reviewed and accepted by the scientific community and with homogeneous data input and output. This last aspect is crucial to be able to compare and combine the results of the various models.

IASPEI (Seismology, Geophysics)

S10c - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-3938

Impact of thermal infrared satellite data on operational earthquake forecast: A long term study over Greece, Italy SW-USA and Taiwan

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Up to now no one measurable parameter, no one observational methodology has demonstrated to be sufficiently reliable and effective for the implementation of an operational earthquake prediction system. However the combined use of independent observations (together with suitable data analysis methods) is expected to strongly improve quality of seismic hazard estimation in the short (weeks) and very short (days) term. Before integration an independent assessment of each considered parameter should be performed in order to establish the strength of its (possible) correlation with earthquake occurrence and its relative weight in a multi-parametric OEF scheme. In this paper long-term analyses of TIR satellite radiances over European (Italy and Greece), American (California) and Asian (Taiwan) regions will be presented. In order to discriminate normal (i.e. related to the change of natural factor and/or observation conditions) fluctuations of Earth's emitted Thermal Infrared (TIR) radiation from anomalous transients (possibly associated to earthquake occurrence), the RST (Robust Satellite Technique) approach has been applied. Its specific potential, when applied in the framework of a multi-parametric OEF system continuously integrating independent observations, will be moreover discussed.

IASPEI (Seismology, Geophysics)

S10c - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-4674

Results and features of sesmic forecasting experiments for Kamchatka and Japan regions

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Results of seismic forecasting using empirical scheme of short-term earthquake prediction are discussed. Since 2002, all 6 officially registered predictions with M7+ for Kamchatka zone are realized without missing events and false alarms including the strongest earthquake of May 24, 2013. Five of these 6 earthquakes were deep focus with epicenters located in the Okhotsk Sea. They occurred around the new moons and full moons ±3 days.

Since 2011, for Japan zone for 15 occurred earthquakes with M6.3+, 13 had official predictions with one missing event (Feb 02, 2013, Hokkaido, M6.9) and one event (Sep 04, 2013, Idzu, M6.4) when monitoring wasn't performed. In several cases, it was noted lowering of predicted magnitudes caused by nearby passages of typhoons or appearance of anomalous ring cloud structures (ARCS).

For the first time, ARCS having nearly perfect semicircumference form with diameter of 300km was observed on May 02, 2013 at the south of Okhotsk plate near Tokyo Bay. Lately, ARCS were observed in the Japan region regularly enough, specifically, before earthquakes of March 02 and 13, June 30, July 11, 2014. These events have lesser magnitudes then their values, predicted by the empirical scheme. Retrospectively, ARCS having concentric circles form were revealed on the satellite images of Feb 19, 2011 in the region of epicenter of Tohoku mega-earthquake of March 11, 2011.

Authors consider these ARCS as the possible indicators of active experiments of forced tectonic stress release, conducted by Japan geophysicists. Possible physical mechanisms of ARCS generation and consequences of these experiments are discussed.
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IASPEI (Seismology, Geophysics)

S10c - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

IUGG-5168

The next great earthquake around Tabriz, Iran

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Tabriz is located in north-west Iran where the deformation is characterized by E–W striking reverse and thrust faults, oblique strike–slip faults as well as N–S striking normal faults. Several aspects of these faults including geometry, slip rates and kinematics are not well documented. Historical data show that several large earthquakes have been occurred in this region and Tabriz and surrounding area with several millions of inhabitants are vulnerable to high seismic hazard. We applied probabilistic analysis of the prediction of the occurrence time of the next great earthquake by maximizing the conditional probability density of earthquake occurrence around the Tabriz city. In order to apply the method we have selected earthquakes with $M>6.0$ and $M>6.5$ in two different radiuses: $r<100$ and $r<150$. Among several distributions that have been already employed for earthquake prediction we have applied the following models: Exponential, Gamma, Lognormal, Pareto, Rayleigh and Weibull. The estimations are accompanied with estimation errors and recurrence times.

IASPEI (Seismology, Geophysics)

S10p - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

S10p-541

Osa-Burica peninsulas, Costa Rica: Attempting to reproduce the success in Nicoya capturing another large earthquake in the near field

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At the Nicoya segment of the Middle American Trench (MAT), off NW Costa Rica, a dense geodynamic control network of seismic and geodetic instruments has been operating, since the 1990s, over the seismogenic zone. At this location the Nicoya peninsula sits right over the seismogenic zone. Campaign and continuous GPS data that expanded for almost two decades were crucial in delineating heterogeneities along the plate interface and anticipating the area where the next earthquake would potentially occur and the magnitude it could reach. These networks successfully captured the pre-, co- and postseismic deformation associated with the Nicoya September 5th, 2012, (Mw=7.6) earthquake; this event may be the best recorded subduction earthquakes in history.

Further south, Osa and Burica peninsulas in SE Costa Rica, also sit over the seismogenic zone. These peninsulas lie only 10 to 30 km from the trench, the angle of the plate interface is shallower than under Nicoya and therefore possesses the potential to produce, though seismic and geodetic monitoring, a very detailed map of heterogeneities along the seismogenic zone and to study the roll of upper plate deformation. This segment of the MAT had produced large earthquakes in 1856, 1904, 1941 and 1983. Mapping and tracking the loading and failure evolution of these medium-size patches could lead to more precise assessments of size, location and timing of future earthquakes. With that purpose, OVSICORI-UNA is building up a dense geodynamic monitoring network on and around Osa-Burica peninsulas to capture and map the rupture area, also in the near field, of a Mw=7.2-7.4

earthquake that will likely occur in the next 10 to 15 years. We will describe the geometry, characteristics and results obtained from these networks.

IASPEI (Seismology, Geophysics)

S10p - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

S10p-542

Forecasting Rates of Large Aftershocks

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Large aftershock forecasting is one of the most important tasks of Operational Earthquake Forecasting. Here we discuss two aspects: 1) application of the Reasenberg-Jones approach to combine aftershock clustering models with Gutenberg-Richter magnitude-frequency relation, and 2) forecasting the large aftershock area. We suggest to use a geometric progression of the forecast time intervals with the beginning and the end multiplied by a factor at each step. This scheme corresponds much better to a power-law temporal decay of aftershocks with an exponent being close to 1. The correction of the model at each step is necessary to take into account often observed temporal change of the b-value, lower catalog completeness right after the main shock and other factors. For the evaluation of the forecasts we apply slightly modified L-test.

Forecasting the aftersock area was never, at our knowledge, considered in terms of operational forecasting. Different declustering models exist to separate post-factum the aftershocks from “independent” events. Large number of studies discussed in previous years the form of the distribution of the afterchocks distances from the mainshock fault. In addition an effect of spatial spreading of the aftershock area was studied. Here we present results of our attempt to assimilate the above researches into a model that can be used in operational aftershock forecasting.

We suggest simple mnemonic rules to forecast the number of large aftershocks on the basis of the number of aftershocks that occurred during first hours after the main shock.This research was supported by Russian Foundation of Basic Research (Projects N 13-05-00158,N 13-05-00541).

IASPEI (Seismology, Geophysics)

S10p - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

S10p-543

The Automated System “Huys” for Current Seismic Hazard Assessment

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The 'Huys' enables us to determine for individual monitoring parameters and their complex area S current seismic hazard and the time interval Δt hazard on the territory of the Republic of Armenia for earthquakes with $M_{max} \geq M \geq 3.5$. Calculated value of the current seismic hazard Z_{cur} in conventional unit) on the territory of Armenia. If the value is equal to or greater Z_{cur} values of the critical seismic hazard Z_{crit} (in the same conventional unit) obtained for the area of long-term seismic hazard in Armenia, with a high probability in the territory of Armenia and neighboring areas could be an earthquake with magnitude $M \geq 3.5$. Magnitude M_{max} for zone S is determined by plotting the cumulative number and magnitude of earthquakes, showing the amount of stored energy that can be released in the current time period Δt in a given area S (Guttenberg-Richter), as well as by graphics and cumulative amount of energy released strain earthquakes with $M \geq 2.5$ (by Benioff).

As a result of the retrospective testing by three monitoring parameters (level of underground water pressure, subsurface radon emission, the intensity of the geomagnetic field) and their complex, the good convergence of the distances between the epicenters of earthquakes tested and calculated areas (locations) of the current seismic hazard, as well as between the calculated times of earthquakes and their real time have been obtained for the 24 seismic events with magnitude $M \geq 3.5$ occurred in the territory of the Republic of Armenia in the period from 1992 to 2012.

IASPEI (Seismology, Geophysics)

S10p - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

S10p-544

Toward a focal mechanism forecasts procedure applied in Italy

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The recognized importance of Probabilistic Seismic Hazard Analysis (PSHA) studies allows us to improve known methodologies. Estimates of long-term worldwide earthquake probabilities based on correlations of seismic moment tensor produced maps showing predicted rate densities for earthquakes occurrence and for focal mechanisms of future earthquakes by Kagan & Jackson (1994). Based on a review of the work described above, we tested a new procedure to compute focal mechanism forecasts integrating moment tensor catalog information with stress field data. The chosen testing area is the Italian territory characterized by a complex tectonic context. In fact, the geodynamic setting of the Italian region is characterized by a complicated interaction of different processes, mainly related to the continental collision between Africa and Eurasia plates and the subduction of Adria microplate beneath the Alps (to the north), Dinarides (to the east) and Apennines (to the west). We used focal mechanism data from the European - Mediterranean RCMT catalogue (http://www.bo.ingv.it/RCMT/searchRCMT.html) combined with stress field indicators from the latest stress map release for Italy (Montone et al., 2012) reviewed and updated.

IASPEI (Seismology, Geophysics)

S10p - S10/S10a Earthquake Prediction: Open session, Operational Earthquake Forecasting

S10p-545

Long-term earthquake forecast for Iran

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Iranian plateau is one of the most seismically active regions in the world and it frequently suffers catastrophic earthquakes. They cause heavy loss of human life along with lots of property damages because of the poor quality of constructions in Iran. In this study, we present a model of earthquake forecasting in Iran to assess the long-term probabilities of future earthquakes with moderate and large magnitudes ($M \geq 5.5$). The model estimates a coupled rate of magnitude, space and time for future seismicity (over a five-year period) using a spatial-temporal Poisson process. We applied the ISC bulletin for the selected region (latitude 25- 41° and longitude 43.5- 64°) in the period of 1970 to 2012. Our results show a meaningful correlation between anomalies of the forecasted seismicity map and the epicenters of target events occurred from 2013 to 2014. Hence, we can conclude that the probable forthcoming earthquakes could be occurred in regions with the highest forecasted seismicity rates and special attention should be given to these anomalies.

IASPEI (Seismology, Geophysics)

S10ba - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-1503

Earthquake predictability, present scenario and future prospects in India and neighborhood

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Improved understanding of fault behavior, responsible urban planning, and advances in building construction have greatly reduced the threat to life from earthquakes, yet more could be done to reduce our exposure to their hazards. Generally, prediction can be completed by stochastic way (statistical) /and deterministic (subjective) way. Former includes the anomalies in seismic waves (abnormality in stress drop and shear stress,) while, latter includes anomalies in seismic images (increment and decrement of regional seismicity, appearance of seismic gaps, seismic belts, seismic swarms and anomalies in special value such as b-value). Earthquake Predictability can be defined as Brick by Brick seismic hazard assessment. In order to improve the accuracy of the earthquake prediction, the earthquake prediction mode should be transferred from the statistical mode to the physical mode. The seismic activity method analyses the time, space, and magnitude of the small to medium-size earthquakes that occurred before past strong earthquakes and can be use to predict the future medium-size or strong earthquakes. In this paper, results emphasize based on these methodologies and several predictions for Indian region including latest forecast in Central Himalaya have been made. The Kashmir Earthquake of October 08, 2005 and many of them came true to some level. But surprises and failure is difficult to address at this stage, which can’t be ignored. However, the study highlight that space-time distribution of the earthquakes has enabled to locate potential area where future earthquake may be seated and recommend monitoring of multi-parameter short term precursory signals to make earthquake prediction programs more meaningful.

IASPEI (Seismology, Geophysics)

S10ba - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-2654

Stress and CFS monitoring for improving EQ warnings - illustrating examples from Southern Iceland

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Microearthquake observations can be used for inverting for the complete absolute stress tensor causing each microearhquake. By this each microearthquake is a complete in situ stress tensor observation, 6 parameters. The main assumption is that the crust is quite fractured. This has turned out to give promising and valuable information when tested in Iceland, in a deep mine and in a couple of geothermal sites with induced seismicity. In this presentation I will give some illustrating examples of the results given by the stress method implementated into the SIL-system at IMO in Reykjavik, Iceland. Both examples of the output os the algorithm before a number of EQs in the range 5<M<6.6 during 1998 to 2013, and some examples of stress mapping within the SISZ area will be given and discussed. These examples illustrate both the shortcomings and the possibilities of the method. The main problem is that the foreshocks must be recorded. The method is based on the microearthquakes so with no observations there will be no information. However, when the microearthquakes are recorded the method gives valuable results.

IASPEI (Seismology, Geophysics)

S10ba - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-2669

Multi-sensor observation of pre-earthquake signals and their connection with major seismicity

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We are presenting the latest development in multi-sensors observations of short-term pre-earthquake phenomena preceding major earthquakes. Our approach for pre-earthquake signal validation is the integrated satellite and terrestrial framework (ISTF) and it is based on a joint analysis of several physical and environmental parameters (satellite thermal infrared radiation (STIR), electron concentration in the ionosphere (GPS/TEC), radon/ion activities, air temperature and rocks deformation measurements) that were found to be associated with earthquake processes. The science rationale for multidisciplinary analysis is based on the concept of Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) (Pulinets and Ouzounov, 2011), which explains the synergy of different physical processes and anomalous variations, usually named short-term pre-earthquake anomalies. Our validation processes consist of two steps: (1) a continuous retrospective analysis of two different regions with high seismicity - Taiwan and Japan in 2003-09, (2) prospective testing of STIR anomalies with the potential for M6+ events worldwide. The retrospective tests (100+ major earthquakes, M>5.9, Taiwan and Japan) show STIR anomalies before most of these events. Prospective testing has shown the presence of anomalies before most of the significant (M>6) earthquakes (2013-14). False positives exist and ratios are different for each region, with a significant reduction of false positives as soon as at least two geophysical parameters are contemporarily used. Our findings suggest that prospective testing of physically based pre-earthquake signals provides a short-term predictive power (in all three necessary parameters - location, time and magnitude) for the occurrence of major earthquakes in the tested regions.

IASPEI (Seismology, Geophysics)

S10ba - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-3564

"The dilemma of earthquake prediction and how to solve it"

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The time dependent hazard assessments often named long term predictions are mainly based on repetitions of felt earthquakes through history. The accuracy of time may be of the order of decades and it is only about the largest hazard that may be expected in areas of hundreds of km diameter. Short term predictions have mostly been based on the observation that after earthquakes it was found that there were “precursors” before them. These most “evident precursors” were created in the uppermost 0-3 km of the crust, where cracks and fluid mobility can magnify straining signals but at the same time make difficult to invert the measurements to monitor processes at the depths where the earthquakes nucleate. Variable crustal conditions make it often difficult even to pinpoint the place where nucleation may be starting. So many have concluded: There are observable changes before earthquakes, but we don’t know what they mean until afterwards.

Theoretical and observational findings of multinational earthquake prediction research in Iceland indicate that micro-earthquakes down to and below magnitude zero provide a near continuous information directly from the nucleation depths about local stress changes and start of fracturing, slow slip and instability, to map the pre-earthquake process and create a constitutive relationship which governs it to be extrapolated to near place and near future for warnings. Large “precursors” created in the uppermost crust will also become significant in the final stage, when we know what basic processes are ongoing at depth. A sketch of a warning scheme for continuous watching is presented.

IASPEI (Seismology, Geophysics)

S10ba - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-4255

Magnitude dependent seismic quiescence and following short-term precursors as dilatancy strengthening and breakdown before large earthquakes and their detection

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Various methods have been proposed to detect anomalous seismicity prior to large earthquake occurrence. However, we still seem to be unable to benefit from such information, even though it must be related to the regional stress buildup and the corresponding crustal deformation processes. We need to better quantify the physical link to earthquake occurrence and verify it through observation. We focus first on magnitude dependent seismic quiescence observed in a larger area than the eventual earthquake main fault area detected retrospectively at years scale. Such observations include 1982 Urakawa-Oki earthquake (M 7.1), 1994 Northridge (Mw 6.7), and 2008 Wenchuan (Mw 7.9). We attempt to model the magnitude selectivity with the cellular automata earthquake model proposed by Sacks and Rydelek (1995). This model reproduces the Gutenberg-Richter scaling law with a large magnitude limit determined by the “cell” size, which may be related to fault maturity of the region. We furthermore include the effect of dilatancy hardening to explain the temporal change in the magnitude dependent quiescence. Useful information must come from precursors such as foreshocks, water well level changes, or macroscopic anomalies that occur within days prior to the mainshock (e.g. 1975 Haicheng, 1976 Tangshan, 2008 Wenchuan). We suggest that these observations are related to excess water expelled by dilatancy breakdown that forces the water into the highly permeable mainshock fault to cause its rupture. We propose to add monitoring of vertical strain, which should be more indicative of the regional change in aquifer.

IASPEI (Seismology, Geophysics)

S10ba - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-5019

Is the mainshock magnitude predictable from attributes of short-term foreshocks?

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The mainshock prediction from foreshocks was investigated since the 1960's. A critical issue, however, concerns the physical factors controlling foreshock incidence given that some mainshocks are preceded by foreshocks but others do not. Another critical issue is the prediction of the mainshock magnitude, Mo, from foreshock attributes. It has been found that Mo does not depend on the magnitude Mf of the largest foreshock. Also, Mo is independent on the duration of the foreshock sequence as well as on the total foreshock energy release. We put forward the hypothesis that foreshock activity is a process of tectonic loading that reflects directly the deformation leading to the mainshock generation. This is exactly the opposite of the relaxation process which is evident by the aftershock activity. In analogy to what happens with aftershocks, our investigation was oriented to look after a possible relationship between Mo and the area, Sf, covered by the foreshock activity. Such an analysis, however, requires for good examples of foreshock locations and an algorithm to discriminate foreshocks from the background seismicity, which is taken as reference model under the assumption that in a target area no changes in the seismicity rate, r, and in the G-R b-value are concurrent at significance level exceeding 0.95. When in a target area r increases and b decreases significantly, then foreshocks are detected and their area is determined within the spatial limits where such seismicity changes do not drop below the 0.95 significance level. Good foreshock examples were selected from Greece, Italy, S. California and Japan, covering a Mo range from 4.5 up to 9. A linear relationship was found between log Sf and Mo, similar to the ones established by others for aftershocks.

IASPEI (Seismology, Geophysics)

S10bb - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-0450

A comprehensive study on Rn-222 earthquake precursory role in Iranian plateau

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Variation in earth gas level like radon in soil and groundwater is a proven technique for tracing the changes in stresses due to seismotectonic activities.

In this research, radon concentration was measured continuously / discretely in 52 point all over the Iranian plateau.

Two months of continuous data in SE Iran has been separated and studied. This measurement have been done near Golbaf fault, which has seismically active history in last century, like Bam great earthquake. During this period, few earthquakes have been occurred and radon level varied significantly prior event. Then, the correlation between these variations and seismic parameters has been studied. It was interesting that a short moment prior to each event, radon concentration has been decreased.

Also, based on measuring radon level in different stations simultaneously, a new analytical algorithm that can be used to estimate optimum range of location and magnitude of coming earthquakes has been presented. This algorithm by introducing parameters such as “target zone”, “uncertainty parameter” and “expectation coefficient” calculate outputs such as “estimated area” and “estimated magnitude” for coming event(s). The results of this study can be used in implementation of continuous radon monitoring network for a comprehensive earthquake precursory studies.

Finally, this algorithm has been successfully tested in central of Iran (Tehran and adjacent regions) and also south and southeast of Iran.

This study including radon monitoring and its correlations with seismic events have been done for the first time in Iranian plateau.

IASPEI (Seismology, Geophysics)

S10bb - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-0549

Prediction method based on the seismic noise synchronization with the Earth tides and its application

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The effect of synchronization of the high-frequency seismic noise (HFSN) with the Earth tides during 1-2 months before large local earthquakes was discovered near 20 years ago. First version of the prediction algorithm was used for earthquakes with M≥6.0 and epicentral distance less than 250 km. According this technique the earthquake precursor is long (more than 3 weeks) stabilization of phase shift between chosen wave of tidal gravity potential (the wave O_1 with period 25.82 hours is used now) and harmonic component with the same period separated from the HFSN envelope. Permanent HFSN observations revealed several features. Among them there are 1) synchronization was observed before more weak, but more close earthquakes, 2) sometimes synchronization with duration 1-2 months was broken short time (near 1 week) before earthquake. Probability estimation as important component of earthquake forecasting was not considered in the first version. All these aspects were taken into account under construction of new version of the technique based on the same phenomena. Moreover the new version includes 1) formalized procedure of alarm cancellation after successful prediction or in the case of expected earthquake absence and 2) efficiency evaluation.

The modernization of this technique was based on the HFSN registration in Kamchatka (Russia) during 1992-2014. For this time there are 68 earthquakes with magnitude M≥5.0, 41 - M≥5.5, 19 - M≥6.0, 9 - M≥6.5, which corresponds to conditions of technique. From them 36 earthquakes with magnitude M≥5.0, 25 - M≥5.5, 15 - M≥6.0, 8 - M≥6.5 have studied precursor. Now the warning conclusions are used by Kamchatka Branch of Russian Expert Council for Earthquake Prediction.

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IASPEI (Seismology, Geophysics)

S10bb - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-3273

Revised accelerating moment release

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From simple considerations we propose a revision of the Accelerating Moment Release (AMR) methodology, that we call revised-AMR (R-AMR), with the purpose to improve the capability to predict time of occurrence and magnitude of the mainshock of a seismic sequence. The proposed revision is based on the introduction of a “reduced” Benioff strain for the earthquakes of the seismic sequence where, for the same magnitude and after a certain distance from the main-shock epicentre, the closer events are weighted more according to a distance-weighted relation. For the estimation of the corresponding main-shock magnitude, although this parameter is the weakest of the analysis, we retain the usual expressions proposed by the ordinary AMR method. We then show the capability of the R-AMR through its application to some case studies. The application of the R-AMR methodology provides better and more stable results in detecting the precursory seismic acceleration, than those found by ordinary AMR technique.

IASPEI (Seismology, Geophysics)

S10bb - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-4102

Importance of statistical tools and real-time database for seismo-geochemical studies along different fault zones of Taiwan

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Over the last few years, we focused on the temporal variations of soil-gas composition at established geochemical observatories along the Hsincheng fault in the Hsinchu area, Hsinhua fault in the Tainan areas, and at Jaosi in the Ilan areas of Taiwan. As per the present practice, the data from various stations are examined synoptically to evaluate earthquake precursory signals against the backdrop of rainfall and other environmental factors. For the earthquake prediction the efficiency of an operation system depends not only upon its logical correctness, but also upon the response time. The database has been developed by the established network of continuous soil-gas monitoring stations along different faults covering NW, SW & eastern Taiwan. The data processing includes a low-pass filter to reduce the noise level. It filters out the high frequency noise and daily variation caused by different parameters like measurement uncertainty, background noise, environmental parameters and earth tides. The rolling average and normalization were used to quantify the probability distribution of variation in the data. In recent years manually operating real-time database had been developed and efforts were made to improve data processing system for earthquake precursory studies by changing the operating system from manual to automatic. We tried to replace the business package software 'Visual Signal' to an open source programming language 'R' for the data computing work. “R” is a free software programming language and software environment for statistical computing and graphics. To upgrade our working procedure to integrate our data with the popular and famous open source web application solution stack 'AMP' (Apache, MySQL, and PHP) has been used.

IASPEI (Seismology, Geophysics)

S10bb - S10b Earthquake Prediction: Earthquake Prediction Research

IUGG-4711

Research on anomalies variation of lithosphere magnetic field before and after lushan Ms7.0 earthquake

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Using the 3-term mobile geomagnetic vector data recorded by 104 geomagnetic measuring sites in the north-south seismic belt during 2010 and 2013, We obtained the dynamic variation of the 2-term lithosphere magnetic, and analyzed the dynamic variation characteristics of the lithosphere local magnetic field before and after Lushan M_s7.0 earthquake on Apr. 20, 2013 in Sichuan to research its relationship with the earthquake. The results showed that: (1)Anomalous characteristics was appeared in the magnetic elements of the lithosphere magnetic field before Lushan M_s7.0 earthquake and disappeared after the earthquake; (2)The anomalous space distribution of the horizontal vector before the earthquake showed that the space of geomagnetic anomaly is in the range of 125 km from the epicenters in the process of earthquake preparation; (3)The direction of the vertical vector and tectonic movement of Longmenshan Fault were opposite in the process of earthquake preparation, and vertical vector value is minimum nearby the epicenter, which might be related to the Lushan M_s 7.0 earthquake of pure thrust type.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-357

Influence of friction coefficient and fault parameters on Coulomb stress change calculations

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The North Aegean Sea, Greece, is characterized by high seismicity rate since frequently strong earthquakes (six, M≥6.5 in the 20th century) occurred here. Much scientific effort is devoted to this area because of the recorded damage to islands or to nearest large cities and another reason is that the edge of North Anatolian Fault is submerged beneath Aegean Sea causing major uncertainties to the faults location and earthquake recurrence. The purpose of this work is to investigate the variability of coseismic stress changes for four strong earthquakes (M≥6.5) that occurred in the study area. Calculated stress changes depend on parameters that must be estimated or be assumed. The Coulomb failure criterion ($\Delta CFF=\Delta\tau+\mu(1-B)$), requires an estimate of friction coefficient (μ) and Skempton's coefficient (B) and there are additional uncertainties involving the target fault geometry, strike, dip and rake. Taking into account various value ranges, conclusions may be drawn concerning the effects in ΔCFF changes of frictional variation, strike, rake and dip, either separately or in combination of two or more of them. Given that the aforementioned calculations consume much computation time, the software "Coulomb Stress Application" was developed (a desktop application based on .NET and SQL Server) as a tool to provide a user-friendly way of entering the necessary data and perform a series of calculations that concern μ, B, rake, dip and combined calculations for a wide range of values. The results can be presented and examined in forms of text files and maps of ΔCFF. By performing such calculations the robustness of the Coulomb stress analyses (e.g. likelihood of potential earthquakes) and ΔCFF maps can be improved.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-358

On the real-time earthquake prediction in Kamchatka region by the 1998-2014 data of Kamchatka Branch of Russian Expert Council

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Kamchatka Expert Council was established in 1998 as subdivision of the Russian Expert Council for Earthquake Forecasting, Assessment of Seismic Hazards and Risk. Kamchatka is one of most seismoactive region of the world. More than 25 earthquakes with M>6.0 occurred in 1998-2014. So problem of earthquake and volcano eruption forecasting is important here. Analysis of large earthquake precursors is one of the main functions of the Council. The authors of various methods of earthquake prediction submit their forecasts to the Council. All predictive messages are documentarily recorded. Conclusions about the seismic situation in Kamchatka are delivered to the Government and EMERCOM.

Precursors of large Kamchatka earthquakes 1998-2014 with M>6.0 detected by various kinds of observations and by different methods are shown. Among them there are seismological, geodetic, seismoacoustic, hydrodynamic, hydro- and geochemical, electromagnetic precursors. Total amount of used methods is more than 20. Most of the applied prediction methods give earthquake waiting periods of about 1 month. All forecasts are divided into successful (time, area and magnitude of expected earthquake correspond to real ones), partially successful (2 from 3 expected value of the parameters are true) and false alarms. Significance evaluations are given for some procedures of monitoring.

The presented data about precursors were received by Kamchatka Branch of Geophysical Survey RAS, Institute of Volcanology and Seismology FEB RAS, Institute of Cosmophysical Research and Radio Wave Propagation FEB RAS, Institute of Physics of the Earth RAS (Moscow), and 'Kamchatnedra'. The experience of the documentarily recorded medium-term earthquake predictions made within 17 years using a set of methods is unique.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-359

Heterogeneities of S-wave attenuation field and ring-shaped seismicity structures in the Pamir-Hindu Kush region: possible preparation for large crustal earthquakes

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We have been mapping short-period shear wave attenuation field in the lithosphere of the Pamir-Hindu Kush region. We used a method based on an analysis of amplitude ratio of Sn and Pn waves. Areas of high attenuation were picked out in the regions of Afghan-Tadjik basin, central Hindu Kush and north Pamir. Ring-shaped seismicity structures have been formed in these areas within depth ranges of 0-33 and 34-70 km since 1973. Pairs of such structures are being formed usually in subduction zones prior to large and great earthquakes. In contrast, only shallow ring structures (h=0-33 km) usually can be picked out in continental regions. We estimated magnitudes of large earthquakes, possibly being prepared in these areas, using characteristics of shallow ring structures (length of big axes and threshold magnitudes) and correlation dependences of these parameters on magnitudes of major events, obtained for continental regions. The values of magnitudes Mw for such events are 7.8±0.4, 6.9±0.5 and 6.7±0.8 for the Afghan-Tadjik basin, central Hindu Kush and north Pamir regions correspondingly. By analogy with subduction zones we suppose that ring-shaped seismicity structures are being formed here due to deep-seated fluid migration.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-360

Some possible precursors of lithosphere magnetic field before several earthquakes in the region of North-South Seismic Belt of China

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From 2010, there are several quakes (magnitude >5.0) in the region of north-south seismic belt, the biggest one is Lushan M7.0 earthquake. Almost beginning from the same time, we carry out geomagnetic survey which covered 10 earthquakes of these quakes.

We measure the geomagnetic vector data on more than 221 sites with interval of ~70km (we expand data base to 235 site in 2012) once in each year. We used minute data on 34 observatories of Geomagnetic Network of China to reduce diurnal variations, and used a model based on hourly data during 1995 to 2014 on same observatories and NOC (Natural Orthogonal Component) method to correct secular variations of geomagnetic data in the different year. Then we got interpolated geomagnetic data of the method of Surfer Spline on North-South Seismic Belt, and reduced the main field which is calculated by Chinese Geomagnetic Reference Field and got the lithosphere magnetic field in this region in each year from 2010.

After analysis the spatial and temporal characters of lithosphere magnetic field, we feel that those place with high gradient of magnetic field and its variation are easier to with an earthquake in the next year. Furthermore, if the variations of geomagnetic field are different on both sides, include direction and value, may be a precursor of an earthquake. As we thought about the fault in this region, we even can catch some earthquakes before it broke. The locations of the earthquakes are about or less than 10km away from our circles, radius of which are 50km usually.

As we are not clear the distance between quake and geomagnetic anomaly are caused by the interval of our sites, future work will involve discuss about this distance and how to point out the circles by a function not by eyes and feeling.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-361

A study on the largest subsequent event of damaging Italian earthquakes

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In this study, we investigate the occurrence of largest aftershocks following the most significant earthquakes that occurred in Italy after 1960. We applied a pattern recognition approach using statistical features to forecast whether a subsequent strong earthquake will follow a target event.

We applied some features of the Vorobieva method [Vorobieva et al. (1993) and Vorobieva (1999)] together with a set of new features and applied decision trees as classifiers and k-fold cross validation to evaluate performances. In Vorobieva method, the events are classified in two different classes: events of type A are mainshocks of magnitude M, followed by a subsequent earthquake having magnitude ≥M-1 inside a given space and time window; the other mainshocks are of type B. In this study, we extend this concept to clusters: clusters of type A include at least one event of type A, while the others are of type B. Our analysis suggest that 74% of strongest aftershocks in clusters of type A occur within 10 days from the mainshock. We then used some of the features of the Vorobieva method using this information.

Finally, we discuss how the spatial distribution of the two types of clusters is related to the tectonic style.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-362

Precursors of strong earthquakes in magnetic disturbances

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Investigation of short-time precursors of strong earthquakes in gradient and phase velocity values of ultralow frequency magnetic disturbances (F<1 Hz) is presented. The gradient and phase velocity along the Earth's surface were determined using a group of three high sensitive three-component magnetic stations situated in angles of a triangle at ~5 km distances (magnetic gradientometer). The magnetic gradientometer give an opportunity to define gradient and phase velocity vectors of the ultralow frequency magnetic disturbances. We found anomaly of the gradient and phase velocity values 2-3 months before a strong earthquake. In direction distributions of the gradient vectors new direction to an epicenter of the forthcoming earthquake epicenters appeared, in the phase velocity vectors – from the forthcoming earthquake epicenters.

An anomaly behavior of secular variations of the main geomagnetic field was investigated during 11-year period before the M9 earthquake in Japan on March 11, 2011. During the period, we found four local anomalies in the secular variations. The first three anomalies preceded with earthquakes in 0.5-1 year. The last anomaly is the biggest one that had begun ~3 years prior to the earthquake moment.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-363

Studies of short-term earthquake prediction with astronomical time-latitude observations

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The paper introduces the discovery of the phenomenon that short-term anomalous fluctuation appeared in astronomical time-latitude observation residuals before earthquakes and characteristics of relations between observation residuals of the instruments in different regions and earthquakes around these instruments. The anomalous variations of the local vertical was thought as the main reason of the anomalous fluctuations of observations residuals. The possibility that the phenomenon will become an effective short-term earthquake precursor, the significance of monitoring and studying the vertical variations using astrometric instruments, and current problems in the research are expounded. If observation networks are set up in earthquake-prone area using some astrometric instruments to carry out observations and studies, it is helpful to know which kinds of earthquakes on which kinds of tectonic zones are easier to cause short-term residuals anomalies in instruments that located in which kinds of tectonic zones, what is the main reason for the differences in characteristics of anomalies and interval length between anomalies and earthquakes, and quantitative or semi-quantitative relations between anomalies and three key factors of earthquake; to optimize methods of observation and exacting effective information; and to validate this potential earthquake precursor. Meanwhile, the performance of the instruments which can be used to set up observation network is discussed. The characteristics of a kind of new astrometric instrument developed by National Astronomical Observatories of Chinese Academy of Sciences are presented. Last, suggestion of setting up observation network with the new instruments in earthquake-prone areas, such as north or northwest China, is proposed.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-364

Pre- and post-seismic heating phenomena of soil and waters before and after the 2012 Emilia earthquake: Mechanisms and potential predictors

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The toponym “Terre Calde di Medolla” (literally “warm earths of Medolla”) refers to a farming area, located near Modena town (Emilia-Romagna region, northern Italy) showing high ground temperatures, particularly evident during winter when the snow cover rapidly melts. After the devastating 2012 Emilia earthquake, in this area soil temperatures increased up to 44°C, i.e. 20-25 °C above the local background value and anomalously high diffuse soil fluxes of CH_4 (up to 2,432 g/m^{2}day) and CO_2 (up to 1,184 g/m^{2}day) were measured, especially from sub-circular zones few meters in diameter. Ground heating and gas seepage were spatially correlated, suggesting a close relationship between the two phenomena. The chemical and isotopic composition of the soil gases measured along a 2.5 m deep vertical profile indicated that the high ground temperature was associated to oxidization of diffusely uprising biogenic methane at very shallow levels (< 1 m), a process that occurs in presence of free oxygen and methanotrophic bacteria. This explanation seems to exclude local uprising of hot fluids from depth. In fact, CH_4 oxidation, being exothermic, was able to produce the observed ground heating up. Moreover, this process is consistent with the extremely negative isotopic ($^{13}C/^{12}C$) signature shown by CO_2 discharges from the soil. According to this hypothesis, the heating of shallow groundwater and ground surface described by several witnesses in the area of the May-June 2012 Emilia earthquake could be related to either a co- or post-seismic onset of new areas of CH_4 seepage or an increase of a pre-existing CH_4 fluxes.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-365

Evidence from subsurface fluid to the stage of meta-instability of strong earthquakes

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Identification of short-term and impending precursors, especially the signals which indicate earthquakes are inevitable, is one of the focused issues of earthquake prediction. The tectonophysics experiment and on-site observation test are thought to be the two significant approaches to explore this issue.
The recent results by Ma (2014) of instability experiment with pre-exist fault showed that, (1) the synergism process of fault is actually a process of interaction between different portions of fault; (2) the degree of synergism is an indicator of the stress state; (3) the late meta-instability with high degree of synergism means the inevitable fault slip, at which the stress-time curve and the accumulation of strain-time curve deviates from linearity and change sharply, at same time, rapidly changes of thermal field are observed on the experiment sample.
There have been built a complex observation networks for monitoring earthquake precursors since the 1966 Xingtai earthquake. The earthquake prediction practice based on short-term and impending precursor identification from the networks has also been started from then on. The on-site observation results showed that several to cades days before earthquake occurrence, sharply changes from subsurface fluid, i.g., groundwater level, temperature from wells, gas content both from well water and from soil of fault zone, are alway more easily observed than from other observation apporaches. The distribution of the sharply changes strongly depend on the station configuration and space location of the active tectonics. According to the obove mentioned observation phenomena, an operational earthquake prediction system has been built and there have been more than 20 successful cases accumulated within 40 year practice.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-366

Experimental study of evolution of thermal field in the stage of meta-instability

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Meta-instability stage is the interval between peak moment O and instability moment B according to stress-time curve. Quasi-static stress release is predominant i the prophase of meta-instability stage, and converts to quasi-Dynamic in the anaphase, with A as the turning moment. Identification of the meta-instable stress state is of great significance for earthquake prediction. This article focuses on evolution of thermal field in the stage of meta-instability.

The mechanisms of temperature changes of tectonic deformation according to previous studies are temperature increase or decrease caused by accumulation or release of stress, and temperature increase due to sliding friction. Besides, fractures and damages of rock can also lead to temperature changes. The experiment is performed on a biaxial servo-controlled press machine. Infrared thermal imaging system is used to observe the thermal field variation of both fault and its lateral blocks synchronously. The main results are:

1. Before moment O, the temperature of the specimen increases as a whole, and the fault cannot be detected on thermal images.

2. In the stage of OA, temperature of blocks decreases successively, and temperature of a few regions on fault begins to increase with small amplitude.

3. In the stage of AB, Fault is clearly visible on processed thermal images. Relatively warm regions on fault expand increasingly and synergically and the warming amplitude accelerates suddenly.

4. After instability, temperature along fault quickly increases far above the amplitude before instability. Meanwhile temperature of blocks decreases further.

Mechanisms of temperature changes at different regions are analyzed and variations of thermal field of earthquake cases are discussed in the article.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-367

Statistical analysis of earthquakes after 1999 MW 7.7 Chi-Chi earthquake based on a modified Reasenberg-Jones model

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We investigated the temporal-spatial hazard of the earthquakes after the 1999 September 21 MW =7.7 Chi-Chi shock in a continental region of Taiwan. The Reasenberg-Jones (RJ) model (Reasenberg and Jones, 1989, 1994) that combines the frequency-magnitude distribution (Gutenberg and Richter, 1944) and time-decaying occurrence rate (Utsu et al., 1995) is conventionally employed for assessing the earthquake hazard after a large shock. However, it is found that the b values in the frequency-magnitude distribution of the earthquakes in the study region dramatically decrease from the background value after the Chi-Chi shock and then gradually increase up. The observation of a time-dependent frequency-magnitude distribution motivated us to propose a modified RJ model (MRJ) to assess the earthquake hazard. To see how the models perform on assessing short-term earthquake hazard, the RJ and MRJ models were separately used to sequentially forecast earthquakes in the study region. To depict the potential rupture area for future earthquakes, we further constructed relative hazard (RH) maps based on the two models. The Receiver Operating Characteristics (ROC) curves (Swets, 1988) finally demonstrated that the RH map based on MRJ model was, in general, superior to the one based on the original RJ model for exploring spatial hazard of earthquakes in a short time after the Chi-Chi shock.

IASPEI (Seismology, Geophysics)

S10bp - S10b Earthquake Prediction: Earthquake Prediction Research

S10bp-368

Appraisal and filtrations of the environmental/meteorological parameters on soil gas radon emission using singular spectrum analysis for earthquake precursory study

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In the present study, characteristics of temporal variability of soil-gas radon concentrations at Hsinhua and Hsinchu monitoring stations in Taiwan has been examined using Singular Spectrum Analysis. In order to make continuity and regularity of the data before applying the Singular Spectrum Analysis, the radon data were carefully edited for rare duplicate sampling, gaps and discontinuous jump following intervals of malfunctioning of equipments. Digital filter has been applied in eliminating the long term trend in the data and retains variations of less than 30 days**.** Singular Spectrum Analysis has been used for the identifications/removal of diurnal and semidiurnal variations in soil gas radon time-series data for earthquake precursory study. Periodic (Daily Variations) and Aperiodic (> 1 day to 30 days) variation have been isolated. Pressure and Temperature variation do not appear to influence radon concentrations at Hsinchu monitoring station in any strong manner. Radon emission is strongly influenced by rain events such that peak enhancement occurs ~ 12-15 hours after the rainfall impulse (capping effect). The radon variations at Hsinchu monitoring station exhibit dominant daily variations, which are controlled by atmospheric temperature inducted evaporation in surface water saturated soil (Capping Effect). The causal relationship is marked by a clear phase lag of 2-3 hours in the sense that peak in daily variation of radon succeeds the peak in temperature. Aperiodic variations in soil radon intensity in the range of 2-10 days are negatively correlated with temperature whereas positively correlated with

pressure. However, the negative correlation of the soil radon with temperature is found to be pseudo effect arising due to parallel variation in pressure.

IASPEI (Seismology, Geophysics)

S12a - S12 Ambient Noise

IUGG-0669

Simplified Green's functions for near-surface application and linear inversion

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Most ambient-noise interferometry applications make use of correlations between pairs of stations that are both located at the Earth's surface. These applications therefore typically require comparison with a surface-wave Green's function. While such Green's functions are generally complex and must be numerically computed, there exist simple analytic expressions for certain commonly used empirical scalings. These results allow the approximate calculation of a large class of near-surface Green's functions without lengthy numerical computations. Furthermore, using these approximate Green's functions allows for a simple linearized inversion of surface-wave phase velocity data that eliminates the need for the standard non-linear inversion. These results have applications to both ambient-noise tomography inversions and understanding seismic noise amplitudes from near-surface sources such as rivers and ocean microseism.

IASPEI (Seismology, Geophysics)

S12a - S12 Ambient Noise

IUGG-1540

The crustal structure beneath the Netherlands from ambient seismic noise

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A 3-D shear velocity model of the crust beneath the Netherlands is determined from fundamental mode Rayleigh and Love wave group measurements derived from ambient seismic noise recordings. The data are obtained from a temporary array of broad-band seismometers in and around the Netherlands (the NARS-Netherlands project, 2008-2012) complemented with data from existing networks in the Netherlands, Belgium and Germany. Rayleigh and Love wave group velocity maps were constructed for the period range of 10 to 30 s. The lateral variations in the group velocity maps primarily reflect variations in sedimentary thickness across the Netherlands. The 2-psi Rayleigh wave and 4-psi Love wave fast directions of the group velocity maps are in agreement with the NW-SE direction of maximum compressive stress as well as with the NW-SE dominant direction of faulting in the Netherlands. The frequency dependence suggests that the azimuthal anisotropy is caused by lattice preferred orientation (LPO) of lower crustal minerals.The 3-D shear-velocity model is obtained by inversion of the group velocity maps using the Neighbourhood Algorithm. The results show a top layer that varies in thickness from 2 to 4 km with with a pattern that is similar to the base of the Rotliegend. A midcrustal discontinuity is found at a depth of about 13 km. The Moho appears to be relatively flat with an average depth of 33 km. Radial anisotropy is mainly positive ($V_{sh} - V_{sv} > 0$) for the lower crust. This can be an expression of LPO but also of horizontal layering or lamination. The top layer shows the largest variations in radial anisotropy with distinct areas of negative radial anisotropy that can be attributed to high-density near-vertical faulting in those regions.

IASPEI (Seismology, Geophysics)

S12a - S12 Ambient Noise

IUGG-2205

Seismic study of the crust across the Northern Scandinavian Mountains from ambient seismic noise

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Today the study of seismic ambient noise is a common method for imaging the lithosphere at short periods (3 -30 s). From the cross correlation of a continuous seismic recordings between seismograms at different stations, we extract the surface wave Green's functions and subsequently the dispersion curve which gives us informations about the shear wave velocity between the stations. Here we choose to use this technique in Scandinavia for a study of the crust across the Northern Scandinavian Mountains. This mountain range is a topographic anomaly (peaks above 1 km) in contact with the flat topography of the Baltic Shield (average height around 500 m). Previous studies suggest variations in density within the crust like mechanism for explaining the (isostatic) equilibrium of the mountain range. In this perspective 2 temporary broadband seismic networks (SCANLIPS2 and SCANILSP3D) used for a seismic study of the crust. We use the information from the ambient seismic noise to build a new crustal model in this region. Combining P receiver functions and Rayleigh wave dispersion curves in a joint inversion we find a crustal thickening from West to East (40 km to 50 km) without any obvious influence of the transition from the Scandinavian Mountains to Baltic Shield on the Moho depth. Analysis of SCANLIPS3D network data allows the construction of a localised 3D crustal model . This model gives us the new perspective in the understanding of this topographic anomaly and the contribution of the crust in the dynamic topography.

IASPEI (Seismology, Geophysics)

S12a - S12 Ambient Noise

IUGG-2321

Processing of long-term recordings of seismic noise and joint inversion of phase and group velocities of Rayleigh and Love waves

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Long-term recordings of seismic noise (covering the time period of 2001-2012) from 88 stations distributed on the territory of Czech Republic and close surroundings were processed by standard cross-correlation technique. Resulting station-to-station correlograms were analyzed with respect to extraction of both phase and group velocities of Rayleigh and Love waves. These path-averaged velocities were localized to regular grid points by using 2D seismic tomography thus yielding local dispersion curves in the frequency range of 1/20 Hz - 1/2 Hz. Finally, all local dispersion curves were inverted jointly (Rayleigh+Love waves, group+phase velocities) to provide local 1D layered representations of the geological environment. Additionally, phase and group velocity maps corresponding to selected periods were compared with the geological and tectonic setting of the target area with satisfactory agreement. The applied method is an alternative way to get reasonable information concerning the velocity structure of the Earth in a regional scale.

IASPEI (Seismology, Geophysics)

S12a - S12 Ambient Noise

IUGG-3365

How ocean waves rock the Earth: Two mechanisms explain microseisms with periods 3 to 300 s

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Microseismic activity, recorded everywhere on Earth, is largely due to ocean waves. Recent progress has clearly identified sources of microseisms in the most energetic band, with periods from 3 to 10 s. In contrast, the generation of longer period microseisms has been strongly debated. Two mechanisms have been proposed to explain seismic wave generation: a primary mechanism, by which ocean waves propagating over bottom slopes generate seismic waves, and a secondary mechanism which relies on the non-linear interaction of ocean waves. Here we show that the primary mechanism explains the average power, frequency distribution, and most of the variability in signals recorded by vertical seismometers, for seismic periods ranging from 13 to 300 s. The secondary mechanism only explains seismic motions with periods shorter than 13 s. Our results build on a quantitative numerical model that gives access to time-varying maps of seismic noise sources.

IASPEI (Seismology, Geophysics)

S12a - S12 Ambient Noise

IUGG-3666

A method to retrieve an improved high resolution reflection response from HiCLIMB array recordings of local earthquake scattering coda

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We discuss a method to interferometrically retrieve the body wave reflection response from local high-frequency scattering coda wave fields with the purpose to obtain an input dataset suitable for the application of advanced exploration-type imaging methods. An image derived from a reflection response with a well constrained virtual source would provide deterministic impedance contrasts, which can complement transmission/refraction tomographies. Scattering coda forms a diffusive and isotropic wave field and is sensitive to smaller scale variations, compared to the ballistic part of the earthquake response. The illumination properties of this wavefield strongly rely on the physical properties and characteristic length scales of the heterogeneous subsurface. We have numerically generated scattering coda for a wide variety of 2D models, which has allowed us to establish a relationship between the accuracy, resolution and depth sensitivity of the retrieved reflection response and specific properties of the scattering medium. Examples of these properties are the crustal thickness, Moho reflectivity and the scattering mean free path. It is known that these properties determine the decay of the intensity of the coda with time, as quantified by the coda attenuation factor. In the past, this coda attenuation factor has been mapped over the surface of several areas worldwide. We have decided to work with a dataset acquired by the HiCLIMB array which crosses the border from Nepal to Tibet. The small inter-receiver distance of the array and the coda attenuation factor of the area meet our established requirements for retrieving an accurate and high resolution reflection response.

IASPEI (Seismology, Geophysics)

S12b - S12 Ambient Noise

IUGG-0547

Application of microseisms for the study of magmatic plumbing system in monogenetic volcanic field: evidence from low-frequency microseismic sounding

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We study the configuration of the volcanic plumbing system at Tolbachinsky Dol (regional zone of monogenetic cinder cones of Plosky Tolbachik volcano) based on recording of natural background microseisms by broadband seismometers Guralp CMG-6TD. Tolbachinsky Dol is situated in the Klyuchevskoy volcano group in Kamchatka. The most important historic fissure eruptions were occurred in this area in 1975-76 and 2012-13. To locate the magma chambers and conduits of these eruptions, we have used a microseismic sounding method (MSM) based on the fact that heterogeneities of the Earth’s crust disturb the spectrum of the low-frequency microseisms in their vicinity. So, at the Earth’s surface the spectral amplitudes of definite frequency f above the high-velocity heterogeneities are decreasing, and above the low-velocity ones they are increasing. The frequency f is connected with the depth of a heterogeneity H and the velocity of the fundamental mode of Rayleigh waves $V_R(f)$ through the relation $H \sim 0.4V_R(f)/f$. From these relations, the MSM lets us model the subsurface structure in a 3D context by inverting the amplitude-frequency spatial distribution of the microseismic ?eld of low frequency. We present the images of low-velocity heterogeneities under eruptive fissures, interpreted as crustal zones of fluid permeability: subvertical magma conduits with a set of shallow magma chambers on the depth approximately 2-3 km, 7-8 km and 15-20 km; sublateral magma conduit, marked by shallow local seismicity during the 1975 eruption; changing in 2013-2014 magmatic feeding system of the new 2012-13 fissure eruption. This study was supported by RFBR grant 13-05-00117.

IASPEI (Seismology, Geophysics)

S12b - S12 Ambient Noise

IUGG-2808

Comparison of coseismic and postseismic shear wave velocity changes detected by Passive Image Interferometry for six large earthquakes in Japan

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We analyzed ambient seismic noise recorded in four areas around large crustal earthquakes in Japan (Mw 6.6 – 6.9). The time series in the different areas range from 3.5 years (Iwate region) up to 8.25 years (Niigata region) and include the respective large earthquakes in those areas and the Tohoku-oki earthquake (Mw 9.0). Green’s functions were calculated by correlating the noise of station pairs (cross-correlations) and the noise of the different components of a single station (single-station cross-correlations) in five frequency ranges between 0.125 and 4.0 Hz. The cross-correlation method is more reliable for frequencies below 0.5 Hz, the single-station cross-correlation for higher frequencies. By performing coda wave interferometry on the Green’s functions for each day, coseismic and postseismic velocity changes were estimated. The velocity change curves as a function of time are similar for all earthquakes. They show coseismic velocity drops at the time of the respective earthquakes, followed by a partial postseismic recovery. The coseismic velocity drops are strongest for large frequencies, indicating a superficial effect for most stations. For the large earthquakes, the coseismic velocity changes are most pronounced near the fault zones. For the Mw 9.0 Tohoku-oki earthquake, some velocity changes were even detected in a distance of about 1000 km from the epicenter in Fukuoka prefecture. A modeling of the volumetric strain changes showed that they cannot explain our observations. The observed coseismic velocity drops are better correlated with peak ground velocity (PGV) than with peak ground acceleration (PGA). This supports the interpretation of a partial coseismic destruction in the rock as the source of the coseismic velocity drops.

IASPEI (Seismology, Geophysics)

S12b - S12 Ambient Noise

IUGG-2862

Temporal changes of seismic velocity beneath Japan during and after the Tohoku-oki earthquake from continuous recordings of the Hi-net array.

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We process 2 years of the continuous data from Hi-net for interstation noise correlations. We measure temporal changes of seismic velocity during this period by analyzing the late part (coda) of the correlations computed for each calendar date. We found that an almost instantaneous velocity drop occurred in most of the volcanic areas at the time of the M9 Tohoku-oki earthquake. We interpret this drop as related to the mechanical weakening of the crust by the passing of the strong seismic waves in the regions where high-pressurized fluids are present (Brenguier et al., 2014). When considering the evolution during the next year, we found that the largest decay of velocity is reached after about 35 days after the main shock in the eastern part of japan that is the closest to the coseismic slip region. This region exhibits an instantaneous velocity drop weaker than the volcanic areas. Instantaneous and delayed responses have therefore different spatial distributions. We compare the observed response distributions with geodetic measurements and with the models of deformation proposed for the postseismic response after the Tohoku-oki earthquake.

IASPEI (Seismology, Geophysics)

S12b - S12 Ambient Noise

IUGG-2913

Detecting seismic velocity changes at Sakurajima volcano, Japan by seismic interferometry and coda wave interferometry

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Sakurajima is one of the most active volcanoes in Japan and is monitored by various kinds of geophysical and geological observations. We detect significant seismic velocity increases at northern and eastern flank of the volcano by applying coda-wave interferometry to records at 6 JMA stations from active seismic experiments conducted once a year in 2011-2013. Amounts of the velocity change are decreasing with frequency: at a maximum 0.40% around 4Hz, 0.15% around 8Hz, and 0.05% around 16Hz. We also apply seismic interferometry to ambient noise during 2012 and 2013 to continuously monitor velocity changes. From the vertical-vertical cross correlations in 1-2, 2-4, and 4-8 Hz bands, we find that seismic velocity increases and decreases with a period of several months for all the station pairs. The amplitude of velocity change is at a maximum 2%, 1%, and 0.5% in 1-2Hz, 2-4Hz, and 4-8Hz, respectively. Results from seismic interferometry is consistent with those from coda-wave interferometry. The periodic change in seismic velocity shows a clear correlation with records of an extensometer shown in CCPVE (2014): velocity increase for contraction while velocity decrease for extension. The strain change may be attributed to a volcanic pressure source at a few kilometers beneath the summit. This study shows that combined use of seismic interferometry and coda-wave interferometry is useful to obtain reliable measurements of seismic velocity changes.

Acknowledgments: We used seismograms recorded by JMA. Active seismic experiments were conducted by DPRI, Kyoto University, other 8 Japanese universities, and JMA.

IASPEI (Seismology, Geophysics)

S12b - S12 Ambient Noise

IUGG-4075

Diffuse field theory to compute the dynamic response of a semi-infinite elastic medium

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The pioneering analytical solution for the dynamic response of an elastic half-space for a normal point load at the free surface is due to Lamb (1904). For a tangential load the solution was obtained by Chao (1960). These solutions are integral representations in the radial wavenumber domain. The elastic field produced by an arbitrary load at any depth within the half-space can be expressed in the same fashion. Computations are usually made using the discrete wave number (DWN) formalism and Fourier analysis allows passing to time domain.

The connection between this deterministic problem, namely, the computation of elastic Green´s function and the diffuse field theory has been pointed out by Sánchez-Sesma et al. (2011) in the framework of the partition of the energy injected into a half-space by surface loads. In this communication, we explore the computation of Green functions at the half-space from a set of equipartitioned elastic plane waves including Rayleigh waves. This approach allows for faster computation as compared with DWN.

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IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-369

Analysis of ambient seismic noise recorded by DAFNE/FINLAND temporary seismic array in Northern Fennoscandia

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The main purpose of the DAFNE/FINLAND passive seismic array experiment in northern Fennoscandia was to characterize the present-day seismicity of the Suasselkä post-glacial fault (SPGF) that was proposed as one potential target for the DAFNE (Drilling Active Faults in Northern Europe) project. The DAFNE/FINLAND array comprised the area of about 20 to 50 km and consisted of 8 short-period and 4 broad-band 3-component autonomous seismic stations installed in the close vicinity of the fault area. In our study we use cross-correlating of ambient seismic noise recorded by the array in order to study seismic velocities in the area of the SPGF. The continuous data for the period 1 year were processed in several steps including single station data analysis, instrument response removal and time-domain stacking. The data were used to estimate empirical Green's functions between pairs of stations in the frequency band 0,1-1 Hz and to calculate correspondent surface wave dispersion curves used for analysis of surface wave velocities. In our paper we concentrate mainly on details of our data processing routine and its influence on precision of dispersion curves evaluation.

Seismic instruments for the DAFNE/FINLAND experiment were provided by the Institute of Seismology of the University of Helsinki and by the SGO. The study was partly funded by Posiva Oy and Geological Survey of Finland (GSF).

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IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-370

Various sources of secondary microseisms excitation

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This document is considered as essential material, which comprehensively summarizes and specifies the possible sources of generation of microseisms that were found during our long-term experimental observations and analyses of the characteristics of secondary microseisms.

We started the detail analyses of microseisms recorded at the solitary broad-band seismic station Ostrava-Krásné Pole (OKC) in the Czech Republic, when windstorms Kyrill and Emma hit most of European countries in January 2007 and in March 2008. Later, we encompassed into our analysis seismic stations pertaining to international data centres, i.e. IRIS and ORPHEUS, which supply also some data.

We found during our analysis that the atmospheric depression and the shoaling of the water is not the only mechanism of secondary microseisms excitation. We recognized at least three other mechanisms for excitation of microseisms: 1) strong earthquakes, 2) thermoelastic waves and 3) LOD variations.

The typical annual variations of microseisms amplitude could be independent on the weather. We can explain it by the propagation of annual thermoelastic wave, which has its stress maximum in the seismogenic depths during winter. We found the deep depression, which did not excited anomalous microseisms. We recognized the higher microseisms several days after strong earthquakes (M>8), e.g. in Chile (Feb. 2010), in Mentawai (Oct.2010) and at Tohoku (March 2011). These earthquakes generated deformation waves spreading and recorded at seismic stations over the whole world. Finally, we documented that the anomalously high microseisms have the same distribution as the LOD variations during the year.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-371

Are there relationships between the formation of ore districts and deep velocity structure in the Middle-Lower Yangtze River region?

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By conducting ambient noise tomography together with two-plane-wave tomography in the Middle-Lower Yangtze River region from the data including 14 months continuous ambient noise data and 219 teleseismic earthquake data recorded at 157 broadband seismic stations, we obtain 5-143 s Rayleigh wave phase velocity maps. Then, by inverting these Rayleigh wave velocity maps, we construct a 3-D shear wave velocity model from the surface down to ∼250 km depth in the Middle-Lower Yangtze River region.

The 3-D model shows that in the upper crust, the basin regions including the JiangHan, HeHuai, SuBei, HeFei and NanYang basin, are all featured with low velocities, and the mountain regions with high velocities. We also notice that the high velocity is observed beneath the Dabie orogenic belt in the upper crust in the upper crust, however, but disappears in the lower crust which may imply that the HP/UHP metamorphic rock only concentrated in the upper crust of the Dabie orogenic belt. In the uppermost mantle, our tomography results show that a low-velocity zone at between 100 and 200 km depth has been widely revealed beneath the Middle-Lower Yangtze River Metallogenic Belt. Meanwhile, our results also reveal a pronounced updip low velocity zone with a southwest-northeast strike under the TongLing and NingWu ore districts in a depth range from 200 km to 80 km. The low-velocity zone may represent the hot upper mantle materials in the past due to the partial melts of paleo-Pacific plate or melting of an enriched mantle source induced by the westward subduction of the paleo-Pacific plate and then upwelling of these mantle-derived magmas resulted in the formation of these granitic rocks and coeval ores deposits along the Middle-Lower Yangtze River Metallogenic Belt.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-372

Detection of Subsurface Reflectors beneath Southwestern Japan using Seismic Interferometry

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A seismic interferometry technique was applied to broadband seismic waveform data in southwestern Japan, to detect the subsurface reflections in this region. Vertical and horizontal components of the continuously recorded seismograms of the broadband seismic network, F-net, which consists of 21 seismic stations, were used for the analysis. We calculated the Green's functions among 21 stations in the southwestern Japan using a deconvolution method. In the 0.25–1.00Hz bandwidth, body waves are clearly observed, as well as a surface wave train with an apparent velocity of 2.7km/sec. These body waves are enhanced by taking sum and differences between ZR (Vertical – Radial) and RZ (Radial – Vertical) components after Takagi et al. (2014). We compared these body waves to the theoretical waves and travel times assuming a 1D subsurface structure proposed by previous studies in this region, and were able to identify P and S body waves reflected from the Moho discontinuity.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-373

"Seismic velocity changes associated with volcanic activity at Hakone volcano, central Japan, using ambient seismic noise records"

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Auto-correlation functions of ambient seismic noise are thought to be a powerful tool for estimating temporal change of crustal structure associated with strong ground motion, or volcanic activity. In this study, we investigated the velocity changes at Hakone volcano, central Japan, where remarkably swarm activities were often observed. We tried to estimate the velocity changes during intense seismic activities in 2011 and 2013. The 2011 activity activated immediately after the 2011 Tohoku-Oki earthquake, suggesting remote triggering by dynamic/static stress changes of the Tohoku-Oki earthquake. During the 2013 activity, crustal deformations were detected by the GNSS stations and tiltmeters, suggesting inflation of a Mogi point source at a depth of 10 km and two shallow cracks. We used the continuous velocity waveforms recorded in the period from October 2010 to December 2013. Waveforms applied band-pass filter between 1 to 3 Hz were used to calculate auto-correlation functions by one-bit correlation technique. We obtained fluctuations of the velocity structure by using the stretching method. A gradual decrease of the velocity structure was observed prior to the 2013 activity at a station in the caldera, which is accompanied by the crustal deformations. We also found sudden velocity decrease at a station near fumarolic area just after the beginning of the 2013 activity and the tilt changes. We interpreted the velocity decreases as material change or crustal deformation associated with the volcanic activity. Noticeable velocity decreases were detected at most of stations in and around the volcano after the Tohoku-Oki earthquake. The result might reflect re-distribution of volcanic fluid by the dynamic/static stress changes.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-374

Crustal velocity structure of Jeju Island contrained by ambient noise cross-correlation

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Jeju Island is the largest volcanic island in Korea. Although several studies focusing on surface geology of the island have been done to reveal the origin of it, the detailed history of evolution, especially the origin of the magma developing the island, is not well understood. To solve this problem, studies about the deeper structure of the island are necessary. In case that seismicity associated with volcanic activity is high, the detailed crustal structure of given volcanic region can be easily obtained by local travel time tomography. However it is not the case and an alternative method is required to study the crustal structure of Jeju Island. Therefore, we apply ambient noise tomography, which is independent of the local seismicity level, to develop 3D crustal velocity model of the island. Data used in this study are 1-year long ambient noise (Oct. 2013 to Sep. 2014) recorded by 20 portable and 3 permanent broadband stations installed by Seoul National University, Pukyong National University, Korean Meteorological Agency, and Korea Institute of Geoscience and Mineral Resources. Rayleigh wave group velocity dispersion curve calculated from cross-correlogram of vertical component waveforms recorded at two stations with the longest interstation distance shows that we can reliably measure group velocity up to 20 sec, which is long enough to sample the whole crust because the crustal thickness of the island is about 24 km. In addition, checker board tests indicate that the minimum resolvable size of the anomaly is about 8 km in the whole study region. These observations indicate that the detailed crustal structure can be obtained using ambient noise tomography and our model will provide useful information to reveal the origin of Jeju Island.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-375

Tracking decollment zone and identification of mid-crustal low velocity layer under western part of the Himalaya using seismic tomography

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The ambient noise tomography performed for the NW Himalaya region using recent data of 31 broadband seismic stations reveals a sizeable mid-crustal low velocity layer and clear evidences of decollment zone. In addition surface wave tomography is performed supporting the evidences of low velocity zone. This part of the Himalaya has witnessed devastating earthquakes such as Kashmir earthquake of 2005 and Kangra earthquake of 1905. Rayleigh and Love waves data is utilized to extract dispersion curves for more than 500 paths for each wave. The spatial difference for group velocities is mapped for the periods in the range 4-50 sec. The 2D tomography maps of fundamental mode highlight high lateral variation that may account the sub-surface tectonic deformation, variable crustal thickness and sub-surface structural formation in high mountain zones. These variations are more for higher period and mainly for the paths passing close to India-Tibet tectonic boundary that suggests low velocity for Rayleigh waves for period more than 10 sec. The study based on latest data provides new detail of sub-surface structural setup of the western part of Himalaya. The minimum value of Rayleigh wave velocity close to detachment zone may correspond partly to mineral anisotropy while its existence to the lower part can be due to partial melting. The influence of Moho on the dispersion data suggests that this discontinuity is dipping towards north and in the northern part close to India-Tibet plate tectonic boundary it should be deeper than the efficiency of available data.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-376

Computing sensitivity kernels of noise correlations with respect to noise sources

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Seismic noise correlations are now commonly used to reconstruct the Green functions of the medium. Although traveltimes extracted from such data have been extensively used to image of the Earth interior, only a few studies have attempted to exploit the amplitudes.

In this work, we compute the sensitivity kernels of noise correlations with respect to the distribution of noise sources in PREM. This allows us to investigate to what extent the surface waves reconstructed by noise correlations can be used to retrieve the anelastic attenuation of the medium.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-377

The inhomogeneous noise sources recorded from the non-linear interaction of the ocean current with the continental slope in Northern SCS

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We study the origin of the background seismic noise by cross-correlating of the continuous seismograms recorded at ocean bottom seismometer (OBS) arrays which were deployed across the continental slope in the northern South China Sea where water depth ranges from 1000 to 3500 meters. Both the vertical and hydrophone components are adopted for all available station pairs to determine the normalized background energy flow through the arrays. Our result shows that the noise energy mainly emerges at two spectral bands corresponding to the primary (0.2~0.5 Hz) and secondary (0.8~1.5 Hz) microseisms. These two groups of microseisms may correspond to the energy scattering in different media. The primary spectral peaks can be detected at correlation time functions formed by both vertical and hydrophone components. While the secondary microseisms are better revealed by the hydrophone components which group velocity is measured at 1.5 km/sec. This leads us to speculate that the secondary microseisms are recorded from the ambient noises within ocean water column. On the other hand, the primary microseisms exhibit an extremely low group velocity of ~ 0.4 km/sec, far below the well-known surface wave velocity, which may be the body waves resonating in the shallow unconsolidated sediments. The direction of the noise energy flow shows a systematical pattern at the stations sit along the continental slope, indicating a major noise may be generated from the non-linear interaction of the ocean current with the topographic slope. Whereas another clear land-ward direction is revealed as well at the stations located in the deep sea basin over 3000 meters of water depth. This suggests that, the deep sea currents may play an important role in generating the ambient noise in deep water.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-378

S-wave velocity structures of the Kaohsiung area, Taiwan, using microtremor array data

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The shallow Shear-wave velocities have widely been used for earthquake ground-motion site characterization. Thus, the S-wave velocity structures of the Kaohsiung area are investigated using the array records of microtremors at 26 sites. The dispersion curves at these sites are calculated using the F-K method (Capon, 1969); then, the S-wave velocity structures in the Kaohsiung area are estimated by employing the surface wave inversion technique (Herrmann, 1991). At frequencies lower than about 2 Hz, the propagation directions are concentrated between the northwest and southwest quadrants. The generation of these may be attributed to the ocean waves of the Taiwan Strait. If the S-wave velocity of bedrock is assumed to be 1500 m/sec, the depths of the alluvium in the Kaohsiung area are between 400~1300 m. The depths of the alluvium are thinner along Shoushan Fault and Panpingshan Anticline (NE-SW direction) in the northern Kaohsiung, and gradually increase from this area to north and south. Moreover, the S-wave velocities are higher along this Fault and Anticline, and gradually decrease from the area to north and south at depths less than 2000 m. Our results are in good agreement with the available geological and geophysical information of the area.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-379

Monitoring storms from seismic noise body waves

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In the secondary microseism period band (3-10sec) and in absence of earthquakes, P-waves generated by storms can be investigated by beamforming techniques. We analyze several storms recorded by the Southern California Seismic Network and we show that P-waves are detected only in narrow frequency bands, which depend on the storm intensity. Back projecting the beam maximum enables to follow the storm track and the beam amplitude can be used to monitor the corresponding seismic source.

We first model the P-wave amplitude generated by storms. The sources are generated by the interaction of ocean gravity waves in the vicinity of the storms. We model them as the power spectral density of the pressure derived from the ocean wave model. We then compute the source site effect of the ocean layer. Both pressure and site effect are frequency dependent. Finally we compute the propagation from the source area to the network. We then compute the synthetic beam corresponding to the modeled P-waves and compare them with the measured beams. We show that the model enables to retrieve the beam amplitude with an error of about 10%, well located in slowness.

In order to get more accurate source parameters, we then invert the beam to retrieve the source location, its lateral extent and the power spectral density of the equivalent forces. We show that this method provides an independent seismological measurement of the storm evolution over time.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-380

Estimation of shallow S-wave velocity structure at the northern Taichung area, Taiwan

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The 1999 Chi-Chi earthquake occurred along the Chelungpu fault and induced strong shaking, causing severe damage in the Taichung area. For both theoretical simulations and ground motion predictions in this area, knowing the S-wave velocity structure of sediments is a matter of great importance. Thus, we conduct array measurements at 16 sites at the northern Taichung area. Most of the measuring sites are located between Tachia-Changhua fault and Sanyi-Chelungpu fault. The dispersion curves at these sites are calculated using the F-K method (Capon, 1969); then, the S-wave velocity structures are estimated by employing the surface wave inversion technique (Herrmann, 1991). To understand the variations of the shallow S-wave velocity at the northern Taichung area, we sketch 2D and 3D maps using imaging techniques based on interpolation algorithms. From 2D/3D profiles of subsurface velocity structures, the depth of the alluvium gradually increases from west (Dadu Plateau) to east and from north to south. The results are in good agreement with the geological and geophysical information of the northern Taichung area. Moreover, these inversion results can be used to do ground-motion simulation of this area in the near future.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-381

Convergence of noise correlations for noise source mapping

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We are working on the imaging of ambient noise sources on the basis of noise correlation functions, an observable which is commonly used in ambient noise tomography and in monitoring. The long-term goal of our study is to develop a method for noise source inversion using noise correlations.

As a first step to this aim, we have investigated the asymmetry between the causal and acausal correlation branch, which is commonly thought to be due to non-isotropic source distribution. We found that a measure of this asymmetry, applied to correlations in the Earth's hum period band, and plotted on station-station great circles with the propagation characteristics of Rayleigh waves, reproduces the qualitative characteristics of known hum source seasonality very well.

An important question in the continuation of this work is how well such maps can be resolved in time. Ambient noise tomography studies commonly stack over long observation periods in order to minimize source influence. Contrarily, we would like to keep the stacks as short as possible while still extracting a meaningful signal. Previous results for seismic hum indicate that selected station pairs converge fast to a result consistent with the long-term average seasonal pattern expected for seismic hum.

We now investigate the relation between stack length and convergent signal on microseismic data (where faster convergence is expected due to the larger signal power of microseisms compared to seismic hum) from correlations between the stations of the Swiss broadband network.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-382

High-resolution imaging of the San Jacinto fault zone with a dense seismic array and local seismic noise.

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A highly-dense Nodal array with 1108 vertical (10 Hz) geophone was deployed around the San Jacinto fault zone for ~4 weeks in 2014 in ~ 600 m x 600 m box configuration (nominal instrument spacing 10-30 m) centered on the Clark branch of the fault zone south of Anza. The array continuously recorded local ambient noise from which cross-correlations between each station pair were extracted for imaging purpose between 1 Hz and 20 Hz. Using subarrays made of 25 sensors, double beamforming was applied to separate body waves from surface waves. Focusing solely on surface waves in a first step, dispersion curves for surface wave group velocities are obtained with unprecedented accuracy at each point of a 10-m spacing grid. The data inversion reveals depth- and lateral-variations of local structural properties within and around the San Jacinto fault zone.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-383

On the noise level of the ambient noise cross-correlation function and its applications

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Retrieving the Empirical Green's function (EGF) between two sensors by cross-correlating continuous records is now a popular technique in the community of seismology. Since the derived EGFs are generally used for the tomographic purpose, little attention has been given to a more quantitative description on the noise behavior of the noise-derived cross-correlation functions (CCF). In this study, we have designed a procedure to quantify the original noise level (ONL) for CCFs and applied it to data in Taiwan and Korea. Because ONL is closely related to the source population of noises and EGF's amplitude is sensitive to the excitation strength, combination of both measurements allows us to put unique constraints to the microseisms around Taiwan and Korea, and we show that (1) the expected high source population of PM around Taiwan is well demonstrated by the strong ONL in the period ~6-9 seconds, although the PM signals are not present in the CCF records or the background seismic noises; (2) The dominant microseisms of period 5~10 sec observed in Taiwan and Korea are mostly contributed by PM (primary microseisms), rather than LPSM (long period secondary microseism) proposed by previous studies; (3) The high SPSM (short period secondary microseism) level in Taiwan Strait is mainly caused by the bathymetry effect; (4) The low ONL in the SPSM band implies that sources for these dominant signals in CCFs are likely confined in the near-coast region.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-385

Towards a full waveform ambient noise inversion

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Noise tomography usually works under the assumption that the inter-station ambient noise correlation is equal to a scaled version of the Green's function between the two receivers. This assumption, however, is only met under specific conditions, for instance, wavefield diffusivity and equipartitioning, zero attenuation, etc., that are typically not satisfied in the Earth. This inconsistency inhibits the exploitation of the full waveform information contained in noise correlations regarding Earth structure and noise generation. To overcome this limitation we attempt to develop a method that consistently accounts for noise distribution, 3D heterogeneous Earth structure and the full seismic wave propagation physics in order to improve the current resolution of tomographic images of the Earth.

As an initial step towards a full waveform ambient noise inversion we develop a preliminary inversion scheme based on a 2D finite-difference code simulating correlation functions and on adjoint techniques. With respect to our final goal, a simultaneous inversion for noise distribution and Earth structure, we address the following two aspects: (1) the capabilities of different misfit functionals to image wave speed anomalies and source distribution and (2) possible source-structure trade-offs, especially to what extent unresolvable structure could be mapped into the inverted noise source distribution and vice versa.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-386

Monitoring two medieval towers through ambient seismic noise deconvolutions

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Passive Image Interferometry has been demonstrated to be a valid tool for seismic monitoring of fault zones, volcanic areas, and also buildings. We set up a temporary experiment of continuous seismic monitoring of the two towers of Bologna, Italy, from September, 2013 to April, 2014. These are two adjacent masonry medieval towers, one 97 m and the other one 48 m high, which are the symbol of the city. We installed 8 tri-axial seismic stations at different levels of the towers (5 in the taller and 3 in the lower tower). For each tower, we performed the deconvolution of the continuous recordings at the base stations from the signals recorded at the different heights, in order to get the Impulse Response Functions (IRF). We analyzed how these functions changed both in frequency and in time. The different IRF shapes for different frequency bands may provide insights in the dispersive nature of wave propagation vertically through the structure. While the IRF changes with time would allow to monitor the temporal variations of the elastic parameters (such as wave velocity), possibly related to environmental factors operating conditions and degradation.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-387

Ambient noise tomography of Europe using data from the VEBSN and temporary arrays

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We use 1-year continuous recordings of waveform data from the Virtual European Broadband Seismic Network (VEBSN) to obtain group and phase velocity maps of Rayleigh and Love waves of Europe and the Mediterranean region. The station coverage of the VEBSN dataset is very dense for most of central and southeastern Europe, while areas of the westernmost Mediterranean and north Africa are less well covered. To compensate for this lack of coverage we incorporate data from temporary array deployments in the westernmost Europe-Mediterranean region, including northwest Africa. With this combined dataset we are able to obtain high resolution dispersion maps for periods from 8 to 40 seconds, that are sensitive to crustal structure, including sediment and crustal thickness. In particular our dispersion maps for short periods image in great detail all major sedimentary basin, with the lowest velocity anomalies corresponding to the North German basin, Po and Adriatic, East Carpathian foredeep, Panonian basin, and the Bay of Biscay. Similarly, dispersion maps for longer periods can be considered as proxies for crustal thickness. Prominent low velocities at longer periods (and therefore greater crustal thicknesses) are observed beneath the Alps, northern Apennines, the Balkans, and the Anatolian Peninsula.

The level of detail of these new maps make them suitable for joint inversion with other types of data (e.g. receiver functions, gravity anomalies) and as starting models for more advanced imaging methods such as full waveform inversion.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-388

Lastarria volcano plumbing using seismic noise tomography to identify the origin of its gases

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Gases at Lastarria volcano have a double origin: hydrothermal and magmatic, as revealed by geochemistry analysis. Nevertheless, the exact location (especially the depth) of degassing is not well known. We show here how seismology may help to answer this question. Hydrothermal and magmatic reservoirs have been revealed by a 3-D high-resolution S-wave velocity tomography deduced from a ambient seismic noise technique at Lazufre (an acronym for Lastarria and Cordón del Azufre), one of the largest worldwide volcanic uplift, both in space and amplitude, located in the Altiplano-Puna Plateau in the central Andes (Chile, Argentine). Past deformation data (InSAR and GPS) and geochemical gas analysis showed a double-wide uplift region and a double-hydrothermal/magmatic source respectively. Nevertheless the location and shape of these sources were not well defined. In this study, we defined them better using seismological data. Three very low S-wave velocity zones are identified. Two of them (with S-wave velocity of about 1.2-1.3 km/s) are located below the Lastarria volcano. One is located between 0 and 1 km below its base. It has a funnel-like shape, and suggests a hydrothermal reservoir. The other one is located between 3 and 6 km depth. Its dyke-shape and depth suggest a magma reservoir that is supposed to feed the shallow hydrothermal system. This double hydrothermal and magmatic source is in agreement with the double-origin found by previous geochemical and magneto-telluric studies. The third low-velocity zone (with S-wave velocity of about 2.7 km/s) located below 6 km depth, is located beneath the center of the main uplift deformation of about 3 cm/yr at Lazufre zone. We suggest it is the top of a large magma chamber previously modeled by InSAR/GPS data.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-389

Subsurface velocity reduction due to the large earthquake that occurred along the north of the Itoigawa-Shizuoka Tectonic Line in Japan

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We observed significant velocity change in the subsurface structure inside the focal area of a large earthquake by analyzing a densely network of seismograms. On 22 November 2014, a large earthquake of M6.7 occurred at northern Nagano, central Japan. The focal area ranged approximately 20 km in length and was located along the Itoigawa-Shizuoka Tectonic Line (ISTL), where we had deployed the Hi-net stations more densely than other regions to reveal the background seismicity and heterogeneous subsurface structure of the ISTL. In order to investigate the earthquake effects on the subsurface structure, we conducted the interferometry analysis using auto-correlation functions of ambient seismic noise calculated by the one bit correlation method. We selected a time window of 4 – 15 s lapes time for the ACFs to estimate fractional velocity change of the structure by the stretching method. The results clearly showed significant velocity reductions ranged 0.5 – 3 % at the five stations within 30 km distant from the focal area. Three of them are on the aftershock area, and the others locate to the north and northeast of the area. The velocity reduction ranges were not good correlated with peak ground accelerations observed by strong motion seismograms or volumetric strain changes calculated by a fault model from the crustal deformation of the earthquake. This result suggested that the velocity reduction is not caused by one factor such as a strong motion, a volumetric strain change, and others. Various phenomena may control the velocity reduction after the earthquake.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-390

A quantitative method to map the source distribution of microseisms using noise covariograms; a case study from the SNSN

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We introduce a method for mapping the noise-source distribution of microseisms which uses all the information of the covariograms (cross-correlations). This allows us to work with few stations to find the direction of incoming energy. By dividing a network into groups of stations and combining the directions from each group we can constrain the source location. The method is based on an inversion of covariograms' envelopes in the time domain, and therefore it is an iterative linearized inversion. The inversion relies on a well known feature of noise cross-correlation, i.e., an anomaly in the noise field can be seen as variation of cross-correlation amplitude in correlograms with the angle between inter-station and noise anomaly directions.
We derived a forward calculation based on the plane-wave assumption in 2D and a homogeneous earth model. The forward calculation involves bandpass filtering of the covariograms. Therefore, the final result of the inversion is the distribution of ambient noise sources in different frequency bands. We demonstrate results of the method based on one year (2012) of data from the Swedish National Seismic Network (SNSN). After preprocessing and cross-correlation, the stations divide into 5 groups of 9 to 12 stations. We invert the envelopes of each group in 8 frequency bands between 2 to 25 sec. Preliminary results show that the noise sources lie predominantly near the Scandinavian margin of the north Atlantic and in the Barents sea.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-391

Extracting traveltime information using a multi station cross correlation technique

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Extracting traveltime information between two seismic stations is a common task in seismology. With ambient noise, two-station cross correlation methods are a common way to extract such information. These methods are, however, subjected to the fundamental assumption that the noise is equipartitioned in different directions. Seismograms from an array of seismic stations are often affected by complex noise fields due to non uniform noise source distributions or the complex geological structures underneath the seismic stations. Therefore, the above assumption is often not satisfied. Recently, the concepts from array processing, e.g., beam-forming, have been incorporated into ambient noise cross correlation in order to improve the signal-to-noise ratio and therefore give better traveltime measurements. We follow the same line of thought and propose a multi-station cross correlation method. This method utilizes information from an array of seismometers, instead of a pair of stations, to obtain more accurate phase information, relaxing the assumption that the noise field is uniform. Theoretical and synthetic analysis on the multi-station cross correlation method are done. In addition, we are investigating if the technique can be applied to the receiver function.

IASPEI (Seismology, Geophysics)

S12p - S12 Ambient Noise

S12p-392

Determination of surface wave group and phase velocities in south Niigata prefecture, Japan using long-term continuous seismic waveform data

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We determined surface wave propagation velocities in an active fold area of south Niigata prefecture for validating the three-dimensional velocity structure model. In this area a continuous seismic array that consists of 15 broadband-to-strong motion stations, extending about 50 km east-west and about 15 km north-south has been in operation since September 2011 (Yoshimi and Hayashida, 2012). First we applied seismic interferometry to the 37-month ambient noise data (September 2011 - November 2014) to extract Green's functions between two stations (105 pairs) for vertical-vertical (Z-Z), radial-radial (R-R), transverse-transverse (T-T), Z-R and Z-T components, in accordance with the widely-used signal processing (Bensen et al., 2007). The signal-to-noise ratios (SNRs) of the cross-correlation functions (CCFs) generally increase with stacking number, especially for Z-Z component and all the stacked CCFs yielded Rayleigh- and Love-wave group velocity dispersions in the frequency range of 0.1-0.7 Hz. We also estimated phase velocities of surface waves using both event data and long-term ambient noise data in the frequency range of 0.05-0.2 Hz. The obtained surface-wave dispersion curves as well as Green's functions are compared with theoretical ones from existing structure models (e.g. Sekiguchi et al., 2009). The results show that years of long-term continuous data provide reliable information on spatial variation of subsurface structure beneath the area.

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IASPEI (Seismology, Geophysics)

S13a - S13 Terrestrial Heat Flow

IUGG-1035

Evaluation of shallow temperature logs for urban heat island effects in Switzerland

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It is customary now in Switzerland to use wireless temperature logging to provide subsurface information for designing large borehole heat exchanger fields. Many of these temperature logs exhibit strong upward curvature in the top 100-150 meters. Data from an area of 3000 km^2 in and around Zurich with areas of various building construction densities and histories show locally clearly different deviations from a linear depth dependence. The significantly different temperature-depth profiles cannot be attributed to climatic warming since it would affect the entire investigated area in a uniform way.

Contrary to these findings, temperature profiles measured in deep wells (decades ago, mostly in sparsely populated areas) show no curvature but trend to mean annual temperature at zero depth.

Therefore it is concluded that the curvatures in shallow boreholes could be attributed to the urban heat island effect. Currently detailed investigations are underway to relate the observed temperature log curvatures to the local history of building construction and use. First result will be presented.

IASPEI (Seismology, Geophysics)

S13a - S13 Terrestrial Heat Flow

IUGG-1090

Over two decades of ground-air temperature tracking: the effect of different land cover materials

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Under applied micropaleoclimate studies to understand the downward propagation of the ground surface temperature (GST) signal into the shallow subsurface a shallow hole (38.3 m) was drilled in 1992 on the campus of the Geophysical Institute in Prague (50º02´28.5'E, 14º28´40.2' N, 274 m a.s.l.). Later, in 2002 a complex polygon site was added to monitor subsurface temperatures under several different surfaces (sand, grass, clay and asphalt) within the uppermost 0.5 m thick layer. (i) The results proved similarity for all investigated depth levels. In addition to the annual wave all measured series proved a complex pattern including 8- and 11-year-long periodicities. (ii) Long-term air temperature records confirmed a pronounced warming rate of 0.0664 K/yr. (iii) Soil temperature monitored at 2 cm depth provides a good estimate of the “skin” surface ground (z=0) temperature, temperature differences between soil temperature (SGT) at 2 cm depth and air temperature (SAT) measured at 5 cm height above surface can be used for the assessment of the ΔT(SGT-SAT) offset values.(iv) Mean temperature offset values ΔT(SGT-SAT) average for asphalt 4.08±0.21 K, sand 1.61±0.16 K, clayey soil 1.32±0.12 K and grassy cover 0.24±0.22 K. (v) Above standard deviations apply for the annual means. The original 5-minute data of the ΔT(SGT-SAT when averaged over the hourly cycle may vary within the range of two to three tens of degree.(vi) The incident solar radiation is the primary variable in determining the ΔT(SGT-SAT) and it increases differently for each of the studied surface cover, the highest rate is typical for asphalt (3.31 K/100 $W.m^{-2}$), for sand cover (1.21 K/100 $W.m^{-2)}$ and for clay cover (1.00 K/100 $W.m^{-2}$). Grass cover proved an opposite tendency and decreases by 0.44 K/100 $W.m^{-2}$).

IASPEI (Seismology, Geophysics)

S13a - S13 Terrestrial Heat Flow

IUGG-1630

South Caspian Basin: Temperature Distribution Models

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Temperature distribution in the sedimentary cover of South Caspian Basin is considered in the thesis. Data on soil temperature recorded in meteorological stations in Azerbaijan and shows that climate temperature of has a strong influence on the temperature of the surface layer of the solid Earth. In accordance with the temperature data from the depth of 3.2 m soil temperature stabilizes at a depth of 3-20 m and the depth of the neutral layer in this region is about 20 m. Schematic maps of the temperature distribution in the 'neutral layer', as well as the depth of 'neutral layer' are constructed. Taking into account the fact that depending on geological and especially hydrogeological conditions, the base of the “neutral layer” might be subsided down to 200-300 m and more. The new schematic map of temperature of “neutral layer” of Azerbaijan was plotted based on these data. It is necessary to note that in the Azerbaijan territory the temperature of ”neutral layer” varies from 5 to 19°?. Lower temperatures of 'neutral layer' are explained by the impact of the water layer.

Distributions of borehole temperatures at various horizontal sections and at the borders of sedimentary layers are investigated. In the result of analysis and interpretation of temperature data of the South Caspian Basin and adjacent areas a series of geothermal maps and models were constructed. Based on them, the spatial structure of the thermal field of the South Caspian Basin is revealed.

IASPEI (Seismology, Geophysics)

S13a - S13 Terrestrial Heat Flow

IUGG-2368

Geothermics of climate change – the Utah experience

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Measurements of subsurface temperature provide not only a means for determining the heat flowing out of the Earth, but also clues to past changes in surface temperature. Three decades of research on the geothermics of climate change at the University of Utah have documented the following: (1) borehole temperature profiles yield a direct and integrated measure of surface temperature histories; (2) repeat logging of a set of boreholes over 30 years confirms the transient nature of anomalies and a direct association with climate change; (3) borehole temperature profiles are consistent with regional surface air temperature records at local and regional meteorological stations; (4) 20 years of operating a geothermal-climate change observatory documents the tracking between ground and air temperatures at various time scales – even though daily means between air and ground temperatures may differ by up to 5 °C, the two temperatures track well over longer periods; (5) snow cover, solar insolation, and ground cover produce an offset between mean annual ground and air temperatures but do not influence longer term warming estimates; (6) a method of combining borehole temperatures with meteorological records suggests that the baseline temperature for the Northern Hemisphere was about 0.7±0.1°C below the 1961-1990 mean with total warming to 2015 now approaching 1.2 °C; and (7) the solid Earth is storing 1.7×10^{22} J due to warming. These results combined with complementary and additional borehole temperature findings from other laboratories worldwide provide compelling evidence for the value of geothermics in global studies of climate change.

IASPEI (Seismology, Geophysics)

S13a - S13 Terrestrial Heat Flow

IUGG-3486

Effects of subsurface warming on thermal storage in Asia

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Subsurface temperature are increased globally because of global warming and anthropogenic impacts such as heat island effects due to urbanization. The increased subsurface temperature may cause additional impacts as subsurface warming on subsurface environment including bio-ecological impacts in soils, however the increased subsurface thermal storage can be used as additional energy source for such as heat pump system. In this studies, increased subsurface temperature due to subsurface warming were compiled in Asian cities, from the point of view of additional energy source in subsurface thermal storage. The impacts of subsurface warming reached to more than 100 meter depth from the surface in some cities in Asia including Tokyo. In this study, global warming as well as subsurface warming is addressed as energy and environmental nexus issue.

IASPEI (Seismology, Geophysics)

S13a - S13 Terrestrial Heat Flow

IUGG-3896

Anthropogenic heat fluxes into subsurface urban heat islands

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Subsurface urban heat islands contain large quantities of energy stored in the form of elevated groundwater temperatures that are caused by anthropogenic heat fluxes into the subsurface (AHF_S). The objective of this study is to quantify the spatial distribution of these AHF_S and the thermal power they transport into the urban subsurface. Thus, statistical and spatial analytical heat flux models for two German cities (Karlsruhe and Cologne) were developed. These models include 2D spatial representations of various sources of AHF_S: (1) elevated ground surface temperatures, (2) basements, (3) sewage systems, (4) sewage leakage, (5) subway tunnels, and (6) district heating networks. The results show that district heating networks induce the largest local AHF_S with values > 60 W/m² and one order of magnitude higher than the other evaluated heat sources. Only sewage pipes and basements reaching into the groundwater cause equally high heat fluxes, with maximal values of 40 W/m² and 14 W/m², respectively. On a citywide scale, basements and elevated ground surface temperatures are the dominant sources of thermal power. A variance analysis confirms that basement depth is the most influential factor to citywide thermal power for cities with a high groundwater table (here 5 m below surface). The spatial distribution of thermal fluxes, however, is mostly influenced by the prevailing thermal gradient across the unsaturated zone. Overall, 2.2 ± 1.4 PJ and 1.0 ± 0.3 PJ of thermal energy are annually transported into the shallow groundwater of Karlsruhe and Cologne due to various AHF_S. This energy serves as a sustainable geothermal potential that is sufficient to cover significant parts (32% and 9%, respectively) of the annual residential space heating demand in both analyzed cities.

IASPEI (Seismology, Geophysics)

S13b - S13 Terrestrial Heat Flow

IUGG-0265

Interplay of porous media and fracture stimulation in Sedimentary Enhanced Geothermal Systems, Red River Formation, Williston Basin, North Dakota

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Fracture stimulated enhanced geothermal systems (EGS) can be installed in both crystalline rocks and in sedimentary basins. The Red River Formation (Ordovician), which lies at ~4 km depth in the Williston Basin, is a viable site for installation of sedimentary EGS (SEGS). SEGS is possible there because temperatures in the formation reach 150 degrees Celsius and the permeability is 0.1-38 mD, thereby requiring fracture stimulation. The project has the goals of 1) optimizing the process of fracture stimulation in an SEGS system in the Red River Formation, and 2) determining if the SEGS system to be installed in the Red River Formation is economically viable. GIS analysis has been completed to produce interpolations of heat flow, geothermal gradient, porosity, permeability, temperature, and the depth to the top and to the bottom of the Red River Formation. Itasca’s 3DEC reservoir simulations software utilizes the GIS analysis to model the 3D response of the Red River Formation to fracture stimulation. These models highlight the ideality of the Red River Formation as a site for fracture stimulation. The addition of fracture stimulation to the reservoir increases the amount of heat that can be extracted, such that the improved geothermal production offsets the cost of the fracture stimulation.

IASPEI (Seismology, Geophysics)

S13b - S13 Terrestrial Heat Flow

IUGG-0372

Scaling relations between geothermal resources and subsurface fluid accumulations: A South American Perspective

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Recent advances in analysis of data sets of heat flow and crustal structure in South America have provided new insights into scaling relations between geothermal resources and subsurface fluid accumulations. In crustal blocks affected by magmatic activity, the spatial dimensions of areas with resources and subsurface accumulations of fluids are found to have comparable dimensions. Examples are cordilleran regions of Chile, highlands regions in Bolivia, crustal blocks along the magmatic arc covering western Ecuador, central volcanic belt of Colombia and northern Venezuela. In such areas the resource base per unit area (referred to the accessible depth limit of 3 km) are in the range of 400 to 1000 gigajoules (GJ), while the recoverable resources per unit area are in the range of 40 to 100 GJ. On the other hand, in areas of crust with near normal temperature gradients such association is not so obvious. There are indications that the relations between spatial dimensions of resources and fluid accumulations are a direct consequence of crustal response to tectonic processes. In regions of magmatic intrusions, tectonic processes lead to development of structural features with dimensions comparable to the thicknesses of local crustal blocks, and co-host geothermal and subsurface fluid resources. On the other hand, in regions of low to normal temperature gradients, the spatial domains of subsurface fluid accumulations in sedimentary basins are larger than those of geothermal resources. In such areas, occurrences of thermal springs are not necessarily indicative of exact locations of geothermal resources.

IASPEI (Seismology, Geophysics)

S13b - S13 Terrestrial Heat Flow

IUGG-1856

Continuous Thermal Core Logging for Reservoir Characterization

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Continuous Thermal Core Logging for Reservoir Characterization

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The first experiment in geophysics with continuous thermal profiling on 3,104 full size as-received cores was performed along a total depth interval of 441 m from two wells in the Usinskoye heavy oil field (Timano-Pechora province, Russia). The optical scanning technique was used for the profiling in core storage. As a result, the thermal conductivity and volumetric heat capacity profiles and distributions of anisotropy and rock thermal heterogeneity coefficients along the wells were obtained. The thermal property measurements were supplemented additionally on 323 core plugs studied with three pore filling fluids successively. The experimental data on thermal property profiles were processed jointly with traditional petrophysical logging data. Close correlations were established between the thermal conductivity, volumetric heat capacity, and rock heterogeneity coefficient (from the profiling) on the one part and porosity (from the logging) on the other part. Detailed data on the porosity structure of the reservoir was obtained from the thermal profiling due to much better spatial resolution (about 5 mm) compared to the logging porosity data (about 0.5 m). Variations in mineralogical composition of rock and the pore filling fluid composition were estimated from the thermal profiling results. Oil saturation zonality was qualified from the thermal profiling data. Rock matrix thermal properties were determined that are necessary for reservoir hydrodynamic modeling.

IASPEI (Seismology, Geophysics)

S13b - S13 Terrestrial Heat Flow

IUGG-2473

EGRT-Mobile: a new tool for evaluating in-situ thermal properties of the ground

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Geothermal heat pumps provide reliable and sustainable heating and cooling for any kind of buildings. Prerequisite for an effective installation is a proper dimension of the ground-coupled heat exchanger. This demands, among other parameters, information on the thermal properties of the ground. The common standard Geothermal Response Test (GRT) heats the pipes of the heat exchanger by circulating hot fluid. The heating process is used to determine averages of the thermal conductivity and the borehole resistance. The Enhanced Geothermal Response Test (EGRT) uses a standard telecommunication hybrid cable, which is installed next to the pipes into the borehole. The copper component of the hybrid cable is used for electrical heating and the optical fiber for distributed temperature measurements. Therefore, results are depth dependent and generate additional information for optimized planning: (1) the identification of aquifers and layers with higher or lower thermal conductivities; (2) in undisturbed boreholes (no convection, no paleo-climate effects) the terrestrial heat flow can be determined; (3) conclusions can be drawn on the quality of the filling between pipes and ground. The new EGRT-Mobile is capable to insert the hybrid cable temporarily into one of the pipes. Then, the EGRT-Mobile provides all the results of the EGRT and offers some advantages: it can be performed without a pre-installation of the hybrid cable and the cable can be re-used, making the measurement cheaper. We present first results of the EGRT-Mobile approach and demonstrate with both: FE-modelling and empirical measurements that vertical convection within the pipe because of the heating is negligible and does not affect the results. The application of the method and its potentials are shown.

IASPEI (Seismology, Geophysics)

S13b - S13 Terrestrial Heat Flow

IUGG-4796

Heat flow determinations from BHT data

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Supplementation of conventional heat flow data with estimates derived from bottom-hole temperatures (BHT) obtained during oil and gas drilling has significantly increased areal coverage in regions where data were sparse, but it has introduced data which are inherently inaccurate. Conventional heat flow determinations involve high-precision temperature, depth and thermal conductivity measurements, but BHT data contain significant inaccuracies due to the thermal disturbance of drilling and fluid circulation. We propose a two-step method for processing BHT data that significantly improves accuracy of the derived heat flow. First, accurate data on stratigraphic thicknesses and thermal conductivities are used to project a temperature vs. depth curve that passes through a plot of the mean value of an ensemble of corrected BHTs from wells within a 10 km radius of the selected site. The position of the curve is determined by selecting the optimum heat flow value in the expression for Fouriers law. Where sufficient numbers of the ensemble of BHT data lie within a 100 m depth interval, heat flow is calculated from the harmonic mean thermal conductivity and the linear temperature gradient determined from the average of the corrected BHT data. If the two heat flow values agree, the quantity determined is deemed acceptable. If not, the BHT data are considered unreliable and the site is rejected. The process has been tested by comparison with heat flow determined from five conventional heat flow sites in the Williston Basin and found to be within ± 4 percent of the conventional value.

IASPEI (Seismology, Geophysics)

S13c - S13 Terrestrial Heat Flow

IUGG-0373

Anomalous geothermal belts along passive continental margins of Eastern Brazil and West Africa

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A comprehensive analysis of geothermal data for sedimentary basins in the continental margin of Brazil (CMB) has been carried out. The results obtained have allowed identification of an anomalous geothermal belt, along the entire extent of CMB, characterized by relatively high temperature gradient and heat flow values relative to those of the adjacent continental and oceanic regions. The widths of this anomalous belt are in the range of 150 to 250 km. It is relatively large in the Southern parts compared with those in the Central and Northern parts. The magnitudes of heat flow anomalies (in the range of 70 to 120 mW/m^2) are compatible with those produced by magmatic heat sources at shallow depths in the upper crust. However, the relatively undisturbed structures of overlying sediments and the largely aseismic character of CMB imply that processes of ductile deformation play a major role in magma emplacements. The existence of such elongated high heat flow belts in the coastal regions of passive continental margins is surprising as it departs from the “normal” geothermal field expected for regions confined between segments of Precambrian continental and stable oceanic crust. Analysis of heat flow data for the offshore region of Angola also point to a similar high heat flow belt in the West African continental margin. It implies that the “bonding” between segments of the continental and oceanic lithosphere is relatively weak along continental margins, allowing for mantle exhumation and magma emplacement at shallow depths along the contact zone.

IASPEI (Seismology, Geophysics)

S13c - S13 Terrestrial Heat Flow

IUGG-0429

Terrestrial heat flow in peninsular India: unique characteristics and geodynamic implications

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Indian Land Mass after separation from Eastern Gondwanaland had periods of movements and eventual collision with mainland Asia around 55 m.y.B.P. These events are significant to have caused and cause changes in its thermal regime and other geo-characteristics.

Analysis of available surface heat flow data of Peninsular India reveals that values are not anomalous. Certain high values in Gondwana basins, rifts and lineaments do not seem to be true conductive head flow, as these mostly have advective heat component. Its exposed Cretaceous/ Eocene Deccan Trap Volcanic Province (including data from a deep bore hole) is also characterized with low surface heat flow. However movements of Indian Land Mass may have caused slow melting of its lithosphere roots, swallowing and flexuring of its LAB under some /most parts, thereby causing high heat flow from mantle, which would have resulted in high surface heat flow in many parts of Peninsular India.

Presently available surface heat flow data and a recently reported discovery of diamondiferous Kimberlites synchronous with Deccan basalt volcanism in Mainpur Kimberlitic field in Bastor Craton imply that parts of Indian Land Mass had a cool and thick lithosphere roots at Cretaceous / Tertiary boundary. Is it not a unique characteristic?

This paper attempts by analyzing available geo-data to discuss this unique characteristics of Peninsular India. This is an important aspect to get a good insight into the geodynamics of the Indian Land Mass and its lithosphere thickness.

IASPEI (Seismology, Geophysics)

S13c - S13 Terrestrial Heat Flow

IUGG-0989

Heat flow, thermal thickness of the lithosphere in the North China craton and geodynamical significances

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Heat flow investigations show that only a small cold core is still preserved in the Ordos, western NCC, with low heat flow value of <50 mW/m^2. The mean heat flow in the eastern NCC is ~64 mW/m^2, close to the global continental average. The thermal lithosphere beneath the NCC thins eastward from ~140 km in the west to ~80 km in the east, with similar trend as the seismic lithosphere. However, there is a disparity in thickness between the thermal and seismic lithosphere, which is ~80 km in the western NCC and decreases eastward. 2D thermal conductive/convective model indicates that, a transition layer exists between the conductive solid lithosphere and the convective fluid asthenosphere, which is named as the rheological boundary layer (RBL). Conduction and convection both transfer heat within this region. The thickness of the RBL is mainly controlled by the asthenospheric viscosity (η), but not or slightly influenced by the thickness and thermal regime of the solid lithosphere. RBL thins in direct proportion to lowing of $\log_{10}(\eta)$. The difference between the thermal and seismic lithosphere implies an eastward thinning of the RBL, which could be attributed to the lowering of asthenospheric viscosity due to dehydration of the subducted Pacific Plate. The geothermal regime confirms that the destruction occurred mainly in the eastern NCC, whereas the western NCC was only locally modified.

IASPEI (Seismology, Geophysics)

S13c - S13 Terrestrial Heat Flow

IUGG-0991

It is high time for a new IHFC authenticated Global Heat Flow Database

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Terrestrial heat flow density (or heat flow in short) is a measure of the energy flux outflowing from the interior of the Earth. One of the major tasks of the International Heat Flow Commission (IHFC) of IASPEI is to gather, publish, and assess quality of heat flow measurements as well as other geothermal data of interest. It has been almost a quarter century since the last published compilation and analysis of global heat flow data of Pollack et al. (1993, Rev. Geophys) under the auspices of the IHFC. The Pollack compilation comprises a total of 20,201 heat flow data entries. Tens of thousands of new heat flow measurements have been reported since then. As the IHFC designated global heat flow database custodian for 2007-2011, William Gosnold, with the assistance of Derrick Hasterok, extents the global compilation to include 58,299 measurements from lands and ocean floors. However the Gosnold compilation has not been updated since 2011, and has not been analyzed for a peer-reviewed journal publication. Hamza et al. (2008, Int. J. Earth Sci.), Davies & Davies (2010, Solid Earth), and Davies (2013, Geochem. Geophys. Geosys.) report analyses of two updated versions of global heat flow data compilations, respectively. However, those versions have not been made available to broad earth science community. Heat flow is an important geophysical variable in many disciplinary research areas of Earth's science and engineering. It is high time for the IHFC to compile an updated global heat flow database, to disseminate the new database to the science community, and to mine the updated database for new insights into the variation of heat flow and its geological, geophysical, and geodynamic implications. We call for the support from the geothermal community for this effort.

IASPEI (Seismology, Geophysics)

S13c - S13 Terrestrial Heat Flow

IUGG-1124

Meso-Cenozoic thermal structure of lithosphere in the Bohai Bay Basin, Eastern North China Craton

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The Bohai Bay Basin is the central area of lithospheric destruction and thinning in the eastern North China Craton (NCC). Our study addresses the spatial distribution of the Meso-Cenozoic mantle heat flow in the region of the Bohai Bay Basin based on the thermal history, radioactive heat production rate and thickness of crustal layering. The Meso-Cenozoic thermal history of the basin experienced two heat flow peaks in the late Early Cretaceous and in the middle to late Paleogene, with heat flow values of 82-86 mW/m^2 and 81-88 mW/m^2 respectively, based on the modeling results by thermal indicators of Ro and AFT. The basin has the average present-day heat flow of 64.5±8.1 mW/m^2. The Meso-Cenozoic lithospheric thermal structure of the Bohai Bay Basin transformed from the “cold mantle but hot crust” stage in the Triassic ~ Jurassic to the “hot mantle but cold crust” stage in the Cretaceous and Cenozoic. During the Triassic and Jurassic, the basin was characterized by lower surface heat flow and the mantle to surface heat flow (q_m/q_s) ratios (<50%), which indicate that the mantle was relatively cold and that the thermal structure of the lithosphere was the “hot crust but cold mantle” type. The q_m/q_s ratio began to exceed 50% and finally reached its first peak (63-68%) during the Early Cretaceous. Then, the surface and mantle heat flows decreased simultaneously, but the q_m/q_s were still over 50%. In the Early Paleogene, the surface and mantle heat flow increased rapidly again, and the q_m/q_s reached its second peak (~75%). Afterwards, the q_m/q_s decreased again down to present-day’s 53-61%. The thermal structure revealed that the activity of upper mantle in the eastern of NCC increased significantly accompanied by the strong crustal movement in the Cretaceous.

IASPEI (Seismology, Geophysics)

S13c - S13 Terrestrial Heat Flow

IUGG-5358

Geotherms and thermal parameters from the Curie depth constrained solutions of the one-dimensional Steady-State Heat-Flow equation: A new method

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We have developed a new method of constraining geotherms deep in the crust. Steady-state geotherms are most commonly derived by solving the heat flow differential equation with surface boundary conditions, and do not explicitly involve temperature constraints at depth. In the new method, we incorporate the magnetic Curie depth, derived from the spectral analysis of magnetic anomaly data (using the Defractal Method), as an a posteriori condition into the solution of 1-D heat-flow equation to anchor geotherms at the Curie depth. The Curie depth constraint allows determination of the ratio of radiogenic heat production (A) to thermal conductivity (K). When K is observed or can be estimated from geologic knowledge, A can be calculated. Furthermore, it is possible to renormalize the derived A to the value where radiogenic elements exponentially decrease with depth (the value of A at the surface denoted as As). The renormalization permits comparison of surface observed and computed values of As which we use to validate the method. We crosschecked observed values of As and K against the ratio As/K derived from the method in New Hampshire; the difference between them is <3%. We also compared our cumulative crustal A across the border of Wyoming and Colorado to the values inferred by Decker et al. (Geol. Soc. Am. Bull. 1988); here the differences are on the order of 4 to 7%. Many areas of the world have high quality aeromagnetic data and, therefore, our new method will be useful in constraining lithospheric geotherms and thermal parameters where the steady-state assumption is valid in a regional sense. We also investigate the utility of Curie depths in transient thermal regimes.

IASPEI (Seismology, Geophysics)

S13d - S13 Terrestrial Heat Flow

IUGG-0486

New geothermal data and their correlation with the potential fields and deep structure by DSS profiles in Western Uzbekistan

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A high variability of Heat Flow Density (HFD) is typical for the territory of Uzbekistan. The statistics by our catalog of data (234 wells) show, that the HFD changes from 18 mWm^{-2} (the well Karamurun in the Central Kyzylkum) to 207 mWm^{-2} (the well Jarkamar in NW Fergana)- the largest Adrasman-Chust Heat Flow anomaly with the maximum HFD value known in Western Central Asia. Spatially and genetically this anomaly is connected with the zone of North-Fergana fault. Also the several zones with high HFD as 100 mWm^{-2} are distinguished in the SW spurs of the Gissar and Surkhandarya basin. Thermophysical properties (temperature gradient, thermal conductivity, thermal capacity) of rocks were studied by the profiles DSS-MRW Kokpatas, Muruntau and Tamdy (Central Kyzylkum).The Tamdy DSS profile is the part of the geotransect Basalt2; it is in its range that the contact of hot and cold heat flows, which also correlated with potential fields. More than 25 years in our laboratory study the thermophysical features of rocks. During this period thermal conductivity, thermal capacity from superdeep Muruntau borehole SG-10 and other ore deposits in details studied and generalized. In this connection the computer program**«PercolationCheck» (the Uzbek patent ?DGU 01170),** intended for calculation of conductivity process in rocks on the basis of raster pictures of distribution of elements in the sample, received on microanalyzer JXA-8800R JEOL has been developed. The program determines presence cells of percolation configurations and visually displays on the screen of computer the available in the investigated sample the clusters, their capacity, and presence of one or more connecting clusters, testifying the conductivity of rocks.

IASPEI (Seismology, Geophysics)

S13d - S13 Terrestrial Heat Flow

IUGG-0908

Heat flow, heat production and thermal structure in the Bundelkhand craton: implications for thermal regime beneath the northern Indian shield

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Heat flow measurements have been carried out at 22 sites in the previously uncovered Bundelkhand craton, northcentral India. Low heat flow, 32-41 mW m^{-2}, characterizes the core of the craton, distinct from the generally high heat flow reported from other parts of the northern Indian shield. Radioelemental measurements on 243 core/outcrop samples reveal both large variability and high average heat production for the Neo-Archaean to Palaeo-Proterozoic granites (4.0±2.1 (SD) μWm^{-3}) relative to the Meso-Archaean TTG gneisses (2.0±1.0 (SD) μWm^{-3}). A systematic characterization of thermophysical properties (i.e., thermal conductivity, density and porosity) of all major rocks comprising the craton was carried out. A set of steady-state, heat flow - crustal heat production models representative of varying crustal scenarios in the craton constrain the crustal thermal structure. Mantle heat flow and Moho temperatures are found to be in the range 12-22 mW m^{-2} and 290-420 ^{o}C respectively, similar to those reported for the Dharwar craton in southern India and other similar age provinces. This study therefore provides a case for similar mantle thermal regimes across the northern and southern parts of the Indian shield, in spite of varying surface heat flow regimes. This suggests that, 1) much of the intra-province and inter-province heat flow variations in the Indian shield can be explained by variations in upper crustal heat production, and, 2) differences in the mantle shear wave velocities between the Dharwar craton and Bundelkhand craton cannot be explained by mantle temperature variations only but require differences in mantle composition as well.

IASPEI (Seismology, Geophysics)

S13d - S13 Terrestrial Heat Flow

IUGG-1469

Temperatures and fault slips on the upper surface of the subducting Philippine Sea plate beneath the Kanto district, central Japan

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To elucidate the relationship between interplate temperatures and generation mechanisms for megathrust earthquakes and slow slip events (SSEs) in the Kanto district, central Japan, we performed numerical simulations on the thermal state. We newly developed a 2-D box-type thermal convection model that is able to handle the subduction of two oceanic plates: the young Philippine Sea (PHS) plate subducts following subduction of the old Pacific plate beneath it. To constrain temperatures on the upper surface of the PHS plate, we used high-density Hi-net heat flow data on land. We found that low heat flow in the Kanto district was caused mostly by subduction of the PHS plate. To explain the heat flow distribution in the Kanto district, we incorporated frictional heating at the plate interface, and temperature changes due to surface erosion and sedimentation associated with crustal deformation during the Quaternary into the models. The most suitable pore pressure ratio to explain the heat flow data was 0.98. The thermally estimated seismogenic zone corresponded well to the fault planes of the 1923 Taisho Kanto earthquake and the western half of the 1707 Genroku Kanto earthquake. The eastern half of the fault plane of the 1707 Genroku Kanto earthquake could be divided into two areas; the northwestern fault plane corresponded to the thermally estimated seismogenic zone, whereas the relationship between the southeastern fault plane and interplate temperatures was ambiguous. The off-Boso SSEs occurred on the plate interface at temperatures lower than approximately 250°C, and the slipped region passed through the 150°C isotherm, corresponding to the phase transformation from smectite to illite. This might suggest that the SSEs occurred in relation to a dehydration process.

IASPEI (Seismology, Geophysics)

S13d - S13 Terrestrial Heat Flow

IUGG-1876

New heat-flow observations in a hotspot swell: the Reunion-Mascarene Plateau

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Terrestrial heat-flow information, generally derived from sea-bottom measurements, can be important to validate theories on the origin of hotspot swells. Strikingly, hotspots are characterised by the lack of high heat-flow values. This is often argument against reheating of the lower half of oceanic lithosphere as a mechanism forming the associated swells. However, it was recently argued that the thermal signature of hotspots can be widely obscured by fluid circulation. Other analyses conclude that hydrothermal flow may redistribute heat only near the swell axes and that the small heat-flow anomalies indicate that the mechanisms producing hotspots do not significantly perturb the thermal state of the lithosphere. In this paper, we investigate the heat flow of the Reunion-Mascarene Plateau hotspot area, an aseismic topographic ridge (western Indian Ocean). We review the available sea-bottom heat-flow determinations and present results of the first heat-flow observations on Mauritius Island, which is considered the second youngest island in the long-lived Reunion mantle plume track. Only marine measurements ranked as of high quality were considered in our study. We reprocessed the heat-flow data for the sediment perturbation, assuming a simple model with constant sedimentation rate, and available sediment thickness and seafloor age data. We recorded temperatures in a hole drilled for geothermal exploration and measured thermal conductivity from core samples from the Mauritius Island. Both marine heat-flow data and the new onshore observations confirm the small size of the heat-flow anomaly in the Reunion-Mascarene Plateau, and at the swell axis, perpendicular to the hotspot track, the heat-flow maxima, which should occur for a lithospheric reheating, are not observed.

IASPEI (Seismology, Geophysics)

S13d - S13 Terrestrial Heat Flow

IUGG-2255

Effective mechanisms of heat transport in sedimentary basins at different scales

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To assess which heat transport mechanism is relevant at which spatial scale in and below sedimentary basins we compare results from 3D numerical simulations considering lithosphere-scale conductive heat transport and basin-fill-scale coupled transport of heat and pore fluids. With the case study of the Central European Basin System we assess the influence of (1) different configurations of the deeper lithosphere, (2) the mechanism of heat transport considered and (3) large faults dissecting the sedimentary succession on the resulting thermal field and groundwater flow. Based on this comparison we link the regional and lithosphere-scale to the sub-basin and basin-fill scale while appropriately considering the effective heat transport processes. We find that conduction as the dominant mechanism of heat transport on the scale of the lithosphere is controlled by the distribution of thermal conductivities, compositional and thickness variations of the conductive and radiogenic crystalline crust and of the insulating sediments and by variations in the depth to the thermal lithosphere-asthenosphere boundary. Variations of these factors cause thermal anomalies of specific wavelength. Advective heat transport may additionally control the thermal field on the regional scale within permeable sedimentary layers. In contrast, convective heat transport and heat transport along faults appears to be only of local importance.

IASPEI (Seismology, Geophysics)

S13d - S13 Terrestrial Heat Flow

IUGG-2315

Multiple-scale heat flow anomalies seaward of the Japan Trench associated with deformation of the incoming Pacific plate

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Anomalous heat flow values, higher than that expected for the seafloor age, are pervasively observed on the seaward side of the Japan Trench. The distribution of the high values does not extend beyond ~150 km from the trench axis, indicating that the anomaly is related to deformation of the incoming Pacific plate associated with subduction. The broad high heat flow zone seaward of the trench can be attributed to efficient vertical heat transport by hydrothermal circulation in a permeable layer in the oceanic crust which thickens toward the trench through fracturing due to plate bending (Kawada et al., 2014). Overlapping the broad anomaly, local variations at a scale of a few kilometers were detected through concentrated measurements at some sites. Numerical modeling of hydrothermal circulation showed that such local anomalies could arise from heterogeneity of the oceanic crust, e.g., basement topography and high-permeability faults. For investigation of the origin of the local anomalies, we conducted a dense heat flow survey around 39°N along a seismic survey line normal to the trench in 2014. Measurements were made at intervals of several hundred meters, in an area 60 to 80 km from the trench axis, where immature horst and graben structures are found. The obtained 20-km detailed profile shows a prominent sawtooth-like variation (60 to 110 mW/m2) at a scale of 3 to 5 km. This characteristic heat flow variation has no apparent correlation with the basement topography and faults and might result from local variation in the permeability structure in deeper part of the oceanic crust.

IASPEI (Seismology, Geophysics)

S13p - S13 Terrestrial Heat Flow

S13p-393

Estimation of earth's interior heat flow from spectral analysis of aeromagnetic data of Upper Sokoto Basin, Nigeria

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An estimate of earth’s interior heat flow has been made in the upper part of Sokoto basin, north-western Nigeria (12.5^o - 13.5^o N, 4.0^o - 6.0^o E) from the spectral analysis of aeromagnetic data. Aeromagnetic maps covering the study area were acquired from the Geological Survey Agency of Nigeria and digitized at an equal spacing of 1 km. Regional anomaly was removed from the data by fitting a plane surface polynomial, while the resulting residual data were subsequently divided into 6 overlapped blocks covering different geological parts for the purpose of spectral centroid analysis. The result showed that the depth to the bottom of magnetic sources varied between 16.71 and 19.42 km. Consequently, using Curie-temperature of 580 ^oC and thermal conductivity of 2.5 Wm^{-1} $^oC^{-1}$, the geothermal gradient varied between 29.87 and 34.71 $^oC/Km$ while the ensuing heat flows varied between 74.67 and 86.77 mW/m^2. Thermal structure of the earth’s crust is one of the main parameters controlling geodynamic processes; therefore, this study is crucial for quantitative understanding of the geo-processes and rheological/rock-physics parameters in the study area.

IASPEI (Seismology, Geophysics)

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Meso-Cenozoic thermal-rheological structure in the Jiyang sub-basin, Bohai Bay Basin

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Bohai Bay Basin is located in the eastern of the North China Craton (NNC) and is the center of lithospheric destruction and thinning. In this paper, we constructed the Meso-Cenozoic thermal-rheological structure of the Jiyang sub-basin which is an important part of Bohai Bay Basin. Based on the thermal history and the crustal structure, combined with the equations of linear fraction and creep strength, we simulated the Meso-Cenozoic thermal-rheological structure profiles of the lithosphere in the Jiyang sub-basin. The results show that thermal-rheological structure profiles of the lithosphere is quite different at different geological times, and experienced two lower lithospheric strength in the Meso-Cenozoic. In the early Mesozoic, the lithosphere was of relative rigidity and stable, as featured by large thickness and strength. During the early Cretaceous, as the lithosphere reached a thinning peak, the lithospheric strength decreased significantly and reached a lower value. During the Late Cretaceous, the lithospheric strength increased apparently, but the lithosphere was still unstable. In the early Paleogene, the lithospheric strength decreased rapidly again and reached the low secondly. Afterwards, the sub-basin entered the depressional stage, and the lithospheric strength increased again, eventually the lithosphere became relative rigidity and stable. From the research, we can see that the destruction process of the NNC has a great impact to the thermal-rheological structure of Jiyang sub-basin, and the thermal-rheological structure varies with the lithosphere thermal regime in Meso-Cenozoic.

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Thermal history reconstruction based on vitrinite reflectance and thermochronological data of the Sichuan basin, SW China

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The Sichuan Basin in southwestern China is a superimposed basin comprising terrestrial and marine sediments. It is well known for its abundant petroleum resources. Thermal history reconstruction using paleogeothermal indicators, including vitrinite reflectance (Ro) and thermochronological data (AFT and (U-Th)/He), shows that different structural subsections of the Sichuan Basin have experienced different paleogeothermal episodes since the Paleozoic. The lower structural subsection comprising the Early Paleozoic to Middle Permian (Pz-P_2) successions experienced a high paleogeothermal gradient (23-43?/km) at the end of the Middle Permian (P_2), whereas the upper structural subsection comprising Late Permian to Mesozoic strata underwent a relatively lower paleogeothermal gradient (15- 27?/km) at the beginning of the denudation (Late Cretaceous or Paleocene in the different regions). During the denudation period, the Sichuan Basin experienced a successive continuous cooling. The high paleogeothermal gradient resulted from an intensive thermal event correlated to the Emeishan mantle plume; the heat flow value reached 120 mW/m^2 in the southwestern basin near the center of the Emeishan Large Igneous Province (ELIP). The low geothermal gradient episode with heat flow ranging from ~40-70 mW/m^2 might be related to the foreland basin evolution. The cooling event is a result of continuous uplift and denudation of the basin and differences in thermal evolution may reflect different denudation mechanisms in the northeastern and southwestern parts of the Sichuan Basin.

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Global analysis of heat-flow data in 2015

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The number and the quality of heat-flow measurements continuously increased during the last 50 years. Here, we examine how it has changed our understanding of the Earth heat-loss and tectono-thermal processes. This work is based on a new compilation (NGHF2014), which includes more than 65000 values, covering 18% of the Earth surface (3586 values and 2% in 1960). In both continents and oceans, the arithmetic average and its standard deviation have increased with the data number. This can be explained by a better spatial resolution, deeper measurements and reduction of several bias. The spatially weighted averages also increased, but in a lesser importance: in 1960, heat-flow was 60 and 73 mWm-2, respectively for continents and oceans, and it is now 68 and 90 mWm-2. In addition, the larger number of oceanic measurements allows filtering for low quality and perturbed data. The resulting Earth minimum heat-loss is 40 TW, i.e. 7-8 TW more than what could have been estimated in 1960 and it reaches 44 TW with data filtering. The increasing spatial resolution has also improved our understanding of hydrothermal and tectono-thermal processes at local and global scales. For instance, we show that heat-flow on divergent continental margins evolves in the same way as the nearby oceanic domain, suggesting that the mantle heat-flow is imposed by the oceanic rather than the continental domain. The strong correlations between surface heat-flow and various geological and geophysical observations is used to predict a global 1°x1° heat flow map. We evaluate the effect of the number and the location of heat flow data on the predictions and suggest where new studies are crucial in order to improve global heat-flow maps.

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Measured versus calculated thermal conductivity of high-grade metamorphic rocks - inferences on the lower crust at ambient and in-situ conditions

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The bulk thermal conductivity (TC) of felsic, intermediate and mafic granulites from the Southern Granulite Province, India, is measured at dry and saturated conditions with the optical-scanning method and calculated from modal mineralogy (determined by XRD and EPMA), applying various mixing models. Most rocks are fine- to medium-grained equigranular in texture. All samples are isotropic to weakly anisotropic and possess low porosities (< 2%). Measured TC values range between 2.5 and 3.0 W m^{-1} K^{-1} for felsic granulites, between 2.5 and 3.5 W m^{-1} K^{-1} for intermediate granulites and between 2.4 and 2.7 W m^{-1} K^{-1} for mafic granulites. Rocks representative for the lower continental crust typically display values between 2 and 3 W m^{-1} K^{-1} at ambient temperature and pressure conditions.

Taking advantage of mean values of mineral TCs, the harmonic mean model provides an almost perfect fit, with a mean deviation of −1 ± 6%. The geometric mean model, which does not consider any layering of minerals or pores and, thus, should be in better harmony with the textural characteristics of the rocks from this study, matches the measured TC data similarly well (mean deviation 5 ± 8%), if minimum values of mineral TCs reported in literature are applied. Thus, if appropriate samples (in terms of sample size or physical-chemical-mechanical condition) for laboratory measurement are not available, bulk TC of high-grade metamorphic rocks with low anisotropy and porosity could be assessed sufficiently good from modal mineralogy, using the data sets for mineral TC applied in this study.

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Heat and groundwater flow in the NE sector of the Morocco hot line

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The Moroccan portion of the Atlas chain is characterised by widespread volcanic activity that occurred 14.6-0.3 Ma ago within a SW-NE trending belt, called Morocco Hot Line (MHL). The volcanic belt extends from the Atlantic coast to the Mediterranean Sea. Geophysical modelling relying on the combination of elevation, geoid anomaly and heat flow data indicated that the lithosphere is strikingly thinned beneath the Atlas chain and thus a hot, buoyant lithosphere is required to explain the relief. A mantle plume, extending from the Canary Islands to central Europe, was invoked to account for such a lithosphere thinning. The geochemical features of volcanism are generally consistent with this hypothesis, being mostly intraplate and alkaline, with the exception the NE termination of MHL, where there is evidence of different sublithospheric mantle sources suggesting an origin partly related to subduction processes. This paper focuses on the thermal features of the NE portion of MHL, where a number of geothermal data have been collected over the past two decades. This zone shows high geothermal gradient and heat flow values, which might be related to deep-seated processes. However, it is hydrogeologically characterised by the occurrence of Liassic limestone forming an extensive, often artesian, deep reservoir hosting moderately hot groundwater. The occurrence of a thermal aquifer may boost the temperature gradient in the overlying, impermeable, marly cover, thus locally yielding enhanced heat flow. We therefore carefully revise the available dataset to investigate the contribution of advection. Temperature data available from water and oil wells were reprocessed and analysed in combination with thermal conductivity measurements on a wide set of lithotypes.

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Quantitative analyses of groundwater flow from thermal tests and temperature logs

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Temperature-time curves recorded during thermal tests in borehole heat exchangers are commonly analysed with the infinite line source (ILS) model assuming a purely conductive thermal regime. Results can be biased by the possible occurrence of groundwater flow. We investigated this flaw by simulating temperature-time signals with a moving line source (MLS) model under different hypothesis of Darcy velocity. A random noise was included in the synthetic data obtained with the MLS model in order to mimic high-frequency disturbances caused by several possible sources (e.g. testing conditions and geological variability) that often occur in real signals. The subsurface thermal conductivity, the Darcy velocity and the borehole thermal resistance were inferred by minimising the root mean square error between the synthetic dataset and the model. The calculated thermal and hydraulic parameters were consistent with the "a priory" values. The optimisation procedure was then tested with synthetic signals originated by the ILS model. For a Darcy velocity exceeding 10^{-7} m s^{-1}, it turns out that ILS largely overestimates thermal conductivity. The approach relying on the MLS model was finally tested on temperature-time data from boreholes drilled in sedimentary aquifers. This produced reliable estimates of thermal conductivity, Darcy velocity and borehole thermal resistance. The magnitude of the inferred groundwater flow was checked by means of an independent method based on the analysis of temperature-depth logs recorded under thermal equilibrium conditions. The matching of thermal logs with analytical models incorporating both heat and mass transfer gave Darcy velocities in agreement with those inferred from the analysis with the MLS model.

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Energy Resources of the Some Geothermal Boreholes in Azerbaijan

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A number of thermal springs and thermal water wells are available in the Azerbaijan. The highest temperature (initial temperature 96 ° C) thermal water is obtained from Jarly-3 well that was drilled between the villages of Jarli and Mollakend on the left bank of the Kur river. Currently the water temperature is 92°C, the mineralization rate is 50 g/l at the well head. Flow rate from the well is more than 2000 m3 per day. According to the parameters set in the last period, power capacity of the well is approximately 10 MW (if water is cooled down to 20°C).

One of the high-potential wells is in the thermal area of Nakhchivan Dapidag and temperatures of the natural thermal springs reach to 26.5°C. The wells that were drilled here gave water at a temperature of 41-53°C from the depth of 137-665 m. The water is highly mineralized water (14,3-21,3 g/l). Flow rate of some wells is 25-34 liters per second. The potential power of the wells in this area is 10 MW.

There are thermal springs and thermal water wells in the Absheron peninsula. The most interesting one is drilled in Shikh field. The well (depth 2400 m) produced 68°C temperature mineral water. This water is used for balneology purposes. Potential power of the well reaches up to 1.3 MW.

It is interesting to note that, in many countries of the world, potential energy of each unit of low potential geothermal energy sources varies between 1-4 MW. These types of sources are successfully used and this field is developing rapidly. Therefore, usage of this kind of geothermal energy sources has broad perspectives in Azerbaijan.

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Geochemical assessment of a MgCl2 heat transport fluid to evaluate the feasibility of using geothermal energy from saline systems

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Saline formations have a heat conductivity 2 to 4 times greater than most rocks. Therefore, higher temperatures can be found near salt formations (Petersen and Lerche 1995). These higher temperatures create the potential for geothermal electrical energy production. A heat transport fluid is required to bring the geothermal heat to the surface. The heat transport fluid must demonstrate a low affinity for mineral dissolution and precipitation to avoid dissolving the formation and clogging the piping material. Our project aims to evaluate a geothermal system consisting of two boreholes within the geological setting of the Canadian part of the Williston Basin. A saturated $MgCl_2$-brine is used to transport heat.

Sophisticated numerical modelling using SEAWAT (Guo and Langevin 2002) and PHT3D (Prommer et al. 2003) is used to evaluate $MgCl_2$-brine as a heat exchange fluid. Since solubility is temperature dependent, the model needs to simulate the dissolution and precipitation of salt minerals due to temperature change. Preliminary results, completed under equilibrium conditions suggest a 90°C range where dissolution and deposition will be slow. These temperatures fall within the 80 to 130°C range present in the salt formations.

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Petersen, K., and I. Lerche. 1995. Quantification of thermal anomalies in sediments around salt structures. Geothermics 24 no. 2: 253-268.

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IASPEI (Seismology, Geophysics)

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Synthesis of subsurface temperature information and evaluation of the potential for setting up borehole heat exchanger in Obama Plain, Japan

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A borehole heat exchanger (BHE) is an economically and environmentally friendly technology that is widely used in Europe and North America, but rarely in Japan. One of the reasons for this is the relatively complex topography and geological structure of Japan compared with the above areas. Complex structures produce regional differences in subsurface thermal properties and temperature structures, leading to regional variation in the efficiency of BHEs. Thus, it is important to evaluate the available subsurface heat energy through thermal response tests and/or numerical simulations and to design appropriate systems (depth and the number of boreholes for heat exchange). Geological structures, groundwater properties, and subsurface temperatures are essential input data for these numerical simulations. We performed BHE numerical simulations using measured data and present a new method for constructing a BHE potential map from regional geological structure models for typical Japanese plains. Our target area is the Obama Plain, which is located in the central part of Japan and faces the Sea of Japan. Subsurface temperatures and thermal conductivities at four stations were measured for the BHE numerical simulations. Results of the numerical simulations show that the BHE efficiency increases by 20% when the subsurface temperature increases by 5 °C and the efficiency also increases by 30% when the groundwater flow varies from 0 m/year to 15 m/year.
In addition, the influence of subsurface warming effects on the BHE efficiency through numerical simulations is discussed. We show that subsurface warming effects cause the BHE efficiency of heating to increase.

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Temperature and Heat Flow Data from Azerbaijan

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Geothermal investigations in Azerbaijan began with the 1870s. During this time, accumulated a sufficiently large number of diverse geothermal information. Based on this information, an electronic database is created. Geothermal database includes data on generating heat in the rocks, about thermal properties of rocks, temperature and geothermal gradient, heat flux. The data cover 13 oil and gas regions (OGR) of Azerbaijan; 152 deposits and exploration areas, including 42 offshore and 110 onshore; more than 2,000 wells; more than 12,000 temperature measurements covering a depth of 8060 m (Saatli ultradeep well SG-1); more than 3000 measurements of thermal conductivity of rock samples; 400 analyzes of samples for the determination of radiogenic heat generation; more than 300 heat flow density data.

Thermal parameters are defined at different times, by different methods - the regular regime method stationary method (using the device 'Lambda') by the needle probe, non-contact method of moving heat source.

Special geothermal studies were conducted in the area of the crater over 30 and mud volcanoes. Over 300 temperature measurements were carried out at different depths, sometimes reaching up to 16 m.

A statistical analysis of all collected data, including analysis of interlaboratory dispersion, and was amended taking into account geological, technical, statistical and other factors.

From these data, the power of radiogenic heat generation in the rocks of Azerbaijan varies between 0,32 ÷ 2,27 mW/m^3. Weighted average of radiogenic heat generation according to this data is 0.94 mW/m^2. Density of heat flow in Azerbaijan varies from 16 to 135 mW/m^2, common values of 40-50 mW/m^2. On the Caspian Sea observed local anomalies of heat flow of 130-600 mW/m^2.

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"Heat flow in South Portugal- A review"

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Reinterpretation of old heat flow data or use of new data and new techniques of detection of the temperature under the surface have conducted to new heat flow density values in some regions of the globe. The results show that mean heat flow values are not advisable to make regional models. The work I intend to present is related with heat flow in the South of Portugal.
Tectonically speaking, the region is very complex and was influenced since the Hercynian Orogeny to Alpine Orogeny. Episodes of volcanism,metamorphism and intensive erosion were detected in the region.
We intend to revise the old data, to introduce new data related with thermal conductivity , heat prodution and data obtained studying metamorphic processes. Some models will be presented related with folding, erosion and geological data. New types of data are used in order to understand the actual thermal regime of this zone.

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" Some comments about new heat flow data obtained in West Antarctica and Greenland"

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One of the main problems related with the heat flow density maps is the high number of values in some regions and the existence of large areas without any data. some of the regions mentioned were a great part of Africa, Brazil, China, and regions near the poles (East and west Antarctica and Greenland). In the last years there are works using a mean heat flow value of 45 mW/m^2 (2010) or values of 65mw/m^2 for East and 100 mw/m^2 for West Antarctica (2013). Schroeder et al (2014) presented a minimum average value of 114 mW/m^2 for the geothermal flux and areas with high flux exceeding 200 mW/m^2 in West Antartctica. Petrunin et al (2013) presented a work where heat flow values obtained in Greenland present values between 20 and 40 mW/m^2 in the South and values higher than 140 mW/m^2 in Central Greenland .In the same work is said that the thermal lithosphere thickness varies from 103 km in the west to 60 km in the southeast. The new values must be considered in the calculus of the global heat flux by conduction through the surface of the Earth.

Another important point is related with the effects of these values. Ice is melting in the regions referred. What is the effect or the participation of the heat flow in the ice melting? How can we relate the heat flow data with the climatic and oceanic temperature values? Why was the ice melting detected only now? I think that an interdisciplinary group must work to obtain the necessary answers.

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Thermal logs as a tool for Darcy velocity determination

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We propose a technique for the determination of main hydrogeological parameters and characterization of groundwater flow from thermal logs. This information is essential for the reconstruction of the water circulation path in the potential geothermal reservoirs. Thermal profiles are generally analyzed to infer information on the terrestrial heat flow and the geothermal gradient under the assumption of a purely conductive thermal regime. The methodology here proposed is based on the study of temperature recorded in boreholes affected by advection. From these data it is possible to recognize the presence of water flow in permeable horizons, but also to quantitatively describe it. The analysis is performed by using analytical models of interpretation of heat transport by advection and yields an estimation of the Darcy velocity, a key parameter for the development of hydrogeological models also finalized to the exploitation of low-enthalpy geothermal resources. The hydrothermal parameters are determined by matching temperature and thermal data with analytical models comprising both heat and water transfer. As an example of application, we select the Maggiore Valley, located in hilly area (Asti Reliefs) of NW Italy where an important aquifer occurs.The stratigraphic succession consists of Pliocene marine sediments (Asti Sand, Zanclean) and the Lower Villafranchian Complex (Ferrere and San Martino Unit, Piacentian). The application of the analytical model proposed to temperature data recorded in the water wells, an aquifer relatively warmer, with predominant horizontal flow. The higher flow seems to be located at depths greater than 60 m, within the marine sediments with sandy texture, and the inferred horizontal velocity values ranging from 10^{-6} - 10^{-7} m·s^{-1}.

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Geothermal Climate Change Observatory, South India: Results from first five years of operation

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A geothermal climate change observatory is operational in south India since July, 2009 to study the inter-relationships between subsurface, ground-surface and surface-air temperature datasets. The Observatory is the first of its kind in the low latitude region and is located in the Choutuppal campus of CSIR-National Geophysical Research Institute (17.29 ^{o}N, 78.92 ^{o}E), about 60 km to the east of Hyderabad. Subsurface temperature measurements are being carried out in two boreholes drilled through massive granite to 21 m and 210 m depths respectively, and in a 1.2 m deep hole passing through weathered granite / regolith. Surface meteorological parameters being recorded at the same site include air temperature, relative humidity, precipitation, solar radiation, wind speed and wind direction. Analysis of temperature data in the 210 m deep hole reveals surface ground warming of 0.5±0.1 ^{o}C over the past 92±7 years, which is consistent with the average warming inferred in south India from analysis of borehole temperature records. The salient features revealed by analysis of ground-air temperature data for the first five years are as follows. (i) The ground temperatures measured in the 1.2 m and 21 m deep holes track the diurnal as well as seasonal changes in surface air temperature respectively. (ii) The ground is warmer than air on average; the difference is not constant but varies between -2 to +7 ^{o}C, (iii) the ground-air temperature difference is influenced by incoming solar radiation and monsoon precipitation, (iv) the ground gets warmer by 1.7 ^{o}C for every 100 Wm^{-2} incident solar radiation for the entire duration of record. The study emphasizes the need to operate the observatory for several years to test the ground-air tracking on decadal and multi-decadal time scales.

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High geothermal potential in the eastern Basin and Range, USA

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The Basin and Range tectonic province of the western USA is characterized by high heat flow, young volcanics, and extensive faulting, all of which contribute to a high geothermal potential. We draw attention to the Roosevelt Hydrothermal System (RHS) in central Utah which now supports 35 MWe power production and is slated for expansion to 70 MWe in 2019. The original estimate of heat loss from the system was 60-70 MW_{th}; assuming a reservoir enthalpy of 1180 kJ/kg (270°C water), the pre-development reservoir upflow was about 60 kg/s. Re-evaluation of the temperature data between 100 and 200 m depth in the original shallow thermal gradient wells supports a thermal outflow zone at least 14 km long, and extending 10 km west towards the center of Milford Valley. A deep geothermal exploration well (Acord-1) near the western limit of the outflow has a temperature of 230°C at its total depth of 3.8 km. The higher estimates of predevelopment heat and mass flow from RHS may be indicative of a significant deep geothermal resource hosted in a granite intrusion beneath the region. With the newly defined reservoir area of at least 50 km^2 and a reservoir thickness of 2 km, a conservative heat sweep of only 2% produces a sustainable output of 300 MWe; if this heat sweep can be tripled to 6%, then a GWe-scale power plant may be envisaged. The challenge for further development will be locating or creating adequate permeability in the large volume of hot granite adjacent to the RHS.

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Heat flow in the European Arctic region – preliminary results from a Norwegian - Russian cooperation

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Geothermal data is a potential indicator of crustal architecture and thickness, volcanic activity and, together with other geological and geophysical data, can be used to infer present and past tectonic regimes. Heat flow measurements and inferred models are critical for the oil and gas exploration and production. Currently, a new global database attempted to gather all available geothermal measurements both on continental and oceanic areas (e.g. Hasterock et al., 2011; Davies, 2013). Much more data is available from exploration wells situated in SW Barents Sea and from Russian studies in the Barents and Kara seas (e.g., Khutorskoi et al, 2009). We aim to enhance the regional database of geothermal measurements by adding all Norwegian and Russian data in order to better understand the Barents Sea and neighbouring area crustal structure and evolution. Models of global heat flow based on a global seismic model of the crust and upper mantle (Shapiro & Ritzwoller, 2004) and regional heatflow based on geological age of the crust are discussed in the light of the newly compiled measured heat flow values.

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Present-day heat flow of the Jizhong Depression in Bohai Bay Basin, East China

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As a second tectonic unit of the Bohai Bay Basin, Jizhong Depression is characterized by a dominance of petroleum reserves located in buried-hill traps of Paleozoic and Proterozoic marine carbonates. Present-day thermal regime play an important role for studying the hydrocarbon generation and maturation of a region. In this study, the present-day heat flow data of 130 wells in the Jizhong Depression were calculated based on measured thermal conductivity, borehole systemic-steady or oil-testing temperature and strata data. These heat flow range from 40 to 110 mW/m^2 with a mean of 57.5 mW/m^2. In the Niutuozhen sub-Uplift, the present-day heat flow of the wells X101, X104, D6 and B8 exceed to 90 mW/m^2,which probably resulted from the thermal convection and surface water, and so they were neglected when we analyzed the horizontal distribution feature of the present-day heat flow in Jizhong Depression. Totally, the present-day heat flow increases from west to east in the Jizhong Depression. The present-day heat flow in the western Jizhong Depression range from 45~55 mW/m^2, while that in the eastern Jizhong Depression varies from 65~70 mW/m^2. Moreover, present-day heat flow is controlled by the topography in the Jizhong Depression. Compared with the sub-depressions (Langgu, Baxian and Raoyang), the sub-uplifts (Niutuozhen, Gaoyang, Rongcheng and Wuji) show a higher heat flow value with 60~80 mW/m^2.

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"The role of hydrogeological conditions and thermophysical properties on the evaluation of geothermal exchange potential"

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A multidisciplinary investigation aimed at optimising low enthalpy geothermal plants in the Marche Region (Central Italy) is currently in progress. The main goal is to improve the present-day knowledge of the geological structure, the hydogeological setting and the thermophysical characters of the subsoil and to obtain a better picture of the regional geothermal exchange potential. Since the seasonal climatic variation can affect the temperature and moisture content of the shallower portion of the subsoil, we are focusing our attention on the continuous monitoring of the physical properties of groundwater (temperature and electrical conductivity above all). Moreover, recording of undisturbed temperature-depth profiles in available boreholes is underway. Meanwhile, we have started an extensive campaign of laboratory measurements of thermal conductivity, volume heat capacity, thermal diffusivity, porosity, density and permeability of the several lithologies forming the sedimentary deposits of the Umbria-Marche successions. In this contribution, we present the first results so far achieved concerning the field monitoring and the laboratory experiments. These data will be fundamental for the subsequent implementations of numerical thermal models of the subsoil, which incorporate conductive and advective heat transfer and which can evaluate the behaviour of borehole heat exchangers under different hydrogeological conditions.

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Shallow (0-200 m) Geothermal Atlas in Catalonia (NE-Spain)

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In 2011, the ICTJA and the ICGC published the first Geothermal Atlas of Catalonia (NE-Spain). The limited availability and distribution of relevant data was a main constrain to understand the geothermal regime, therefore we developed an indirect approach estimating a theoretical shallow thermal regime from the lithospheric structure, standard rock parameters and annual climate variation. In a new version of the Atlas focused in the shallow regime, we develop this methodology with the aim to provide a useful evaluation tool to the operating stakeholders. We provide maps for relevant thermal parameters: the background conductive heat flow (Q), calculated from integrated thermal and geopotential modelling; the shallow thermal conductivity (k), from correlation between lithological maps and published values; the surface geothermal gradient (∇T), from the combination of Q and k; the thermal diffusivity (α), from k and standard rock parameters; the surface temperature (To) and seasonal variations, from meteorological station data; the ground penetration of seasonal To variations (Z), from To and α; the calculated temperature distribution from 0 and 200 m deep (Tz) and seasonal variations, from To, ∇T and Z; and finally, the thermal jump between To and Tz and seasonal variations.

The resulting map set provides a theoretical baseline for a shallow (0-200 m) geothermal potential evaluation: a) geothermal provinces partition, b) favoring zones for further exploration, c) efficiency forecasting for geothermal installations, and d) correlation with measured parameters. Convective perturbations link to groundwater circulation are the main expected baseline deviation, therefore the map set interpretation has to be done jointly with groundwater flow map and structural geologic map.

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Anthropogenic signals in transient components of the subsurface temperature field

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The repeated temperature profiles or long-term temperature records from several boreholes in urbanized areas in Czechia (Prague), Slovenia (Sempeter) and Finland (Espoo) were analyzed to assess and decompose contribution of human activities and regional climate changes on subsurface warming detected in a transient component of the temperature profiles at each of the three sites. The observed data were compared with temperatures yielded by mathematical 3D time-variable geothermal models of the boreholes' sites. In the first step, only the surface air temperature changes were taken into account as a boundary condition. In the second step, effect of particular anthropogenic structures was appended. At all the sites a direct human impact on the subsurface temperature warming was proved and contributions of individual anthropogenic structures to this change were evaluated. The strongest effect of human activity is detectable in Espoo, where the borehole is situated directly in the basement of a large building. The impact of urbanization is detectable down to the depth of 150 m here and the share of the anthropogenic signal in the non-stationary component of the observed subsurface temperature amounts to 90% at the depth of 50 m. On the other sites the share of the anthropogenic signal in the non-stationary component of the observed subsurface temperature amounts to 40 percent at the depth of 40 m in the case of Sempeter and to 50 percent at the same depth in the case of Prague.

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Heat flow and interstitial water chemistry in the flanks of the Oceanographer-Hayes segment of the Mid-Atlantic Ridge

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It is currently estimated that a third of the oceanic heat loss is due to fluid circulation in the oceanic crust. Besides the high temperature fluid discharge at ridge axis, the more discrete off-axis fluid circulation involves very large volumes of low temperature fluids. Long term investigations of the Juan de Fuca eastern ridge flank have established a circulation pattern where hydrothermal discharge and recharge occur at basement outcrops. Here, we present results from the Oceanograflu cruise (2013), on the targeted the ridge flanks of the Oceanographer-Hayes segment of the Mid-Atlantic ridge at about 35°N. Hundred and eighty five heat flow measurements were obtained and thirty 3 to 5 meters long Küllenberg cores coupled with temperature gradient measurements were retrieved on both flanks of the ridge. The measured heat flow is generally lower than the conductive cooling model values, but the pattern is rather different from that observed in other locations, with no clear discharge or recharge sites identified at this time. Indeed, many outcrops basement are observed, but heat flow patterns are not consistent with fluid circulation into the oceanic basement like in the Juan de Fuca area. Furthermore, several temperature-depth profiles do not always show linear gradients, but rather sigmoid shapes or inverse gradients. The composition of sediment interstitial waters retrieved by rhizon sampling every 30 cm has been determined in order to look for signs of fluid advection through the sediment that could explain the heat flow pattern. We will present relevant observations and discuss possible processes affecting the heat-flow and the porewater composition in the Oceanographer-Hayes Ridge flanks.

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Recent earthquakes and geologically recent volcanoes in South-west Victoria, Australia

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Australia includes no active plate boundaries so seismicity is low, but relatively fast movement of the plate to the north (~70 mm/year), and very active plate boundaries to the north and east result in high intraplate stress and above average seismicity for a stable continental region.

There are more than 400 volcanic eruption sites in the southwest of Victoria and far southeast of South Australia, a region covering about 400 km east-west and 200 km north-south. The oldest erupted about 4 million years ago, and although there have been no eruptions since European settlement in 1834, the oral history of the aboriginal people who arrived about 50,000 years ago refers to active volcanoes, but without any indication of date. Volcano types include scoria cones, maars, and extensive areas of lava flows on the plains.

In this region, the average recurrence interval of earthquakes exceeding magnitude 5.0 is about 20 years, and exceeding magnitude 6.0 is about 200 years, while that of volcano eruptions is several thousand years.

Most of the larger earthquakes with magnitudes from 5.0 to over 6.5 have been located south of the main volcanic region. Local seismograph networks have been operating since 1990, allowing relatively accurate epicentre locations of more than 2000 smaller events. Although the recording period is a very small fraction of the average recurrence interval for moderate to large earthquakes, the locations of small earthquakes appear to complement the volcano distribution.

This is another example of non-random behaviour of earthquakes in space and time, and the need to understand the geological processes involved when considering earthquake hazard.

There is some correlation between the limited available heat flow data and the location of volcanic regions.

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Radiogenic heat production in paleozoic, mesozoic, and cenozoic sedimentary rocks from the central United States

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Sedimentary rocks typically contain only a few ppm of the primary heat producing elements, uranium and thorium, and a few percent of the radioelement, potassium. Thus, radioactive heat production in sedimentary rocks ranges from a few tenths of a $\mu W/m^3$ in chemical sedimentary rocks to a few $\mu W/m^3$ in siliciclastic rocks. Thicknesses of sedimentary rocks in the basins of central United States range from less than 1 km to greater than 4 km. A common characteristic of the midcontinent basins is that they contain a laterally continuous record of largely carbonaceous Paleozoic rocks covered by siliciclastic rocks of Mesozoic and Cenozoic age. The contribution to heat flow from radioactive heat production in these sedimentary basins could be as high as 12 mW m^{-2} in the Denver and Williston Basins, however, there has been no previous work to determine this.

We used gamma ray spectrometry to analyze continuously collected drill cuttings from 18 heat flow holes that penetrate representative samples of the rocks in the mid-continent basins. Paleozoic carbonates average 1.62 ± 0.27 ppm U, 4.38 ± 0.93 ppm Th and 1.09 ± 0.12 percent K. Mesozoic siliciclastic rocks average 2.40 ± 1.33 ppm U, 6.53 ± 1.56 ppm Th, and 1.41 ± 0.39 percent K. Cenozoic siliciclastic rocks average 2.08 ± 0.52 ppm U, 7.24 ± 1.59 ppm Th, and 1.53 ± 0.31 percent K. These numbers yield heat production values of 1.0, 1.4, and 1.4 mW m^{-2} for Paleozoic, Mesozoic, and Cenozoic rocks respectively and indicate that the radiogenic contribution to heat flow is approximately 5.2 mW m^{-2} to 5.5 mW m^{-2} in the Denver and Williston basins respectively.

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"Environmental pre-exploitation monitoring of Torre Alfina geothermal system (Central Italy)"

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The project of an interesting industrial geothermal pilot plant, with no-gas emission in atmosphere, has been presented for approval in the medium-enthalpy geothermal field of Torre Alfina. This prompted us to develop a geochemical and geophysical monitoring of the area with the aim of establishing a background information to recognize anomalous gas emission, induced seismicity and subsidence, possibly related to the field exploitation. The geothermal reservoir (140°C) is hosted within fractured Mesozoic limestones, covered by an impervious flysch cap-rock. A detailed survey of soil CO_2 flux of the whole geothermal area, and periodic monitoring of target areas near future wells, has shown the effectiveness of the impervious cover, as most of the CO_2 soil emission has a biological origin related to “soil respiration”. Surface emission of geothermal gas (mostly CO_2), as ascertained by chemical and isotopic analyses, occurs only in the proximity of a NW normal fault, where an experimental automatic micro gas–chromatograph has been installed to monitor gas composition with a high analysis frequency. A six station seismic network has been established having as barycentre the future reinjection pole where nearly 1000 tons/hour of geothermal water should be reinjected and hence there is the highest probability of inducing seismicity. A ground deformation system including GPS and InSAR techniques is also planned to monitor possible subsidence. Besides providing useful information on the environmental impact of the planned geothermal plant, the collected geochemical and geophysical data will allow to refine the geological, structural, hydrogeological and thermal model of the zone.

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Thermal regime measured at volcanic areas in Japan

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Borehole temperature profiles and samples in volcanic areas even at shallow depths provide valuable information about the thermal regime. Recently, drilling cores sampled from Japan Meteorological Agency's (JMA's) borehole type volcanic monitoring stations [Group for Drilling Core Analysis, Coordinating Committee for the Prediction of Volcanic Eruption, 2011] offers an opportunity for studying the thermal regime at 42 volcanoes in Japan. Thermal conductivity, heat capacity, and density were measured on 122 samples obtained from these JMA's boreholes. Thermal conductivity shows good correlation with density. Two different types of devices were used to measure thermal conductivities: a line-source device with a half-space type box probe (Quick Thermal Conductivity Meter (QTM), Kyoto Electronics Manufacturing Co.) and an optical scanning device (Thermal Conductivity Scanner (TCS), Popov et al. [1999]). A comparison between the QTM and TCS demonstrates that either method gives the similar value of thermal conductivity at room temperature over the range of 1-3 W m^{-1} K^{-1}. We also obtained continuous temperature profiles from JMA's boreholes up to about 100 m in depth. Because the temperature fields in the shallow part is often perturbed by surface effects, reliable measurements require deep boreholes, at least several hundreds meters. Therefore, although less precise, these data provide most of the estimates of heat flux at volcanic areas in Japan.

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New heat flow determination in northern Tarim Craton, northwest China

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Tarim craton is a Precambrian block situated in northwest China, just north of the Tibetan Plateau, where a large sedimentary basin with abundant hydrocarbon potential has developed. Accurate heat flow data for Tarim is vital for understanding the lithospheric evolution and hydrocarbon generation in this area; however, there were unavailable until now, due to a lack of high quality steady-state temperature logging data. Here, we report 10 new heat flow values derived from steady-state temperature logging and measured thermal conductivity data. New heat flow values range from 40.3 mW/m^2 to 49.4 mW/m^2, with a mean of 43.1±3.0 mW/m^2. In addition, radiogenic heat production from the sediments accounts for 20% of the observed surface heat flow, whilst the mantle heat flow is estimated to be as low as 6~15 mW/m^2; this indicates a dominant contribution from crustal heat, to the observed heat flow. The average heat flow and crustal temperature in the Tarim craton are markedly lower than those in the Tibetan Plateau, whilst the calculated rheological strength of the lithosphere, beneath Tarim, is sufficiently large to resist the elevation-induced gravitational potential energy difference between Tarim and Tibet. This inherited thermal and rheological contrast, between the craton and Plateau, can be traced back to before the India-Asia collision; this accounts for the differential active deformation pattern in the Tarim craton and adjacent areas.